FAA R&D Contract No. DTFA03-02-C-00044
DESTRUCTIVE EVALUATION
AND EXTENDED FATIGUE TESTING
OF A RETIRED PASSENGER AIRCRAFT (B727)

Phase II, CLIN 0002(d), Task 9
Damage Characterization
Q4 Update

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OVERVIEW

- This presentation is on the Damage Characterization results obtained during both Quarters 3 and 4 on three bays of fuselage lap joint; at stringer 4R and bays FS 520-540, 540-560 and 580-600. The presentation is in 4 parts:
  - Part 1
    - Pre-teardown microscopy and measurement results
    - Teardown methodology
    - Stereo-microscopy results after tear down
  - Part 2
    - Rivet installation and Hole quality studies
  - Part 3
    - SEM fractography of cracks including study of origins; fracture surface morphology and fatigue striation measurements;
    - Crack growth rates and estimated life
  - Part 4
    - Conclusions

Part 1: Pre-teardown microscopy and measurements

This was the first step of the characterization process and included stereomicroscope documentation of:

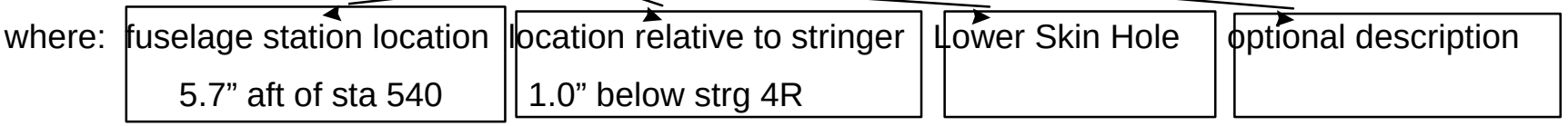
- the joint exterior edge;
- normal views of fastener heads in the outer skin;
- normal and 45 deg tilted internal views of fastener bucked tails;

and dimensional measurements of rivet bucked tail diameters.

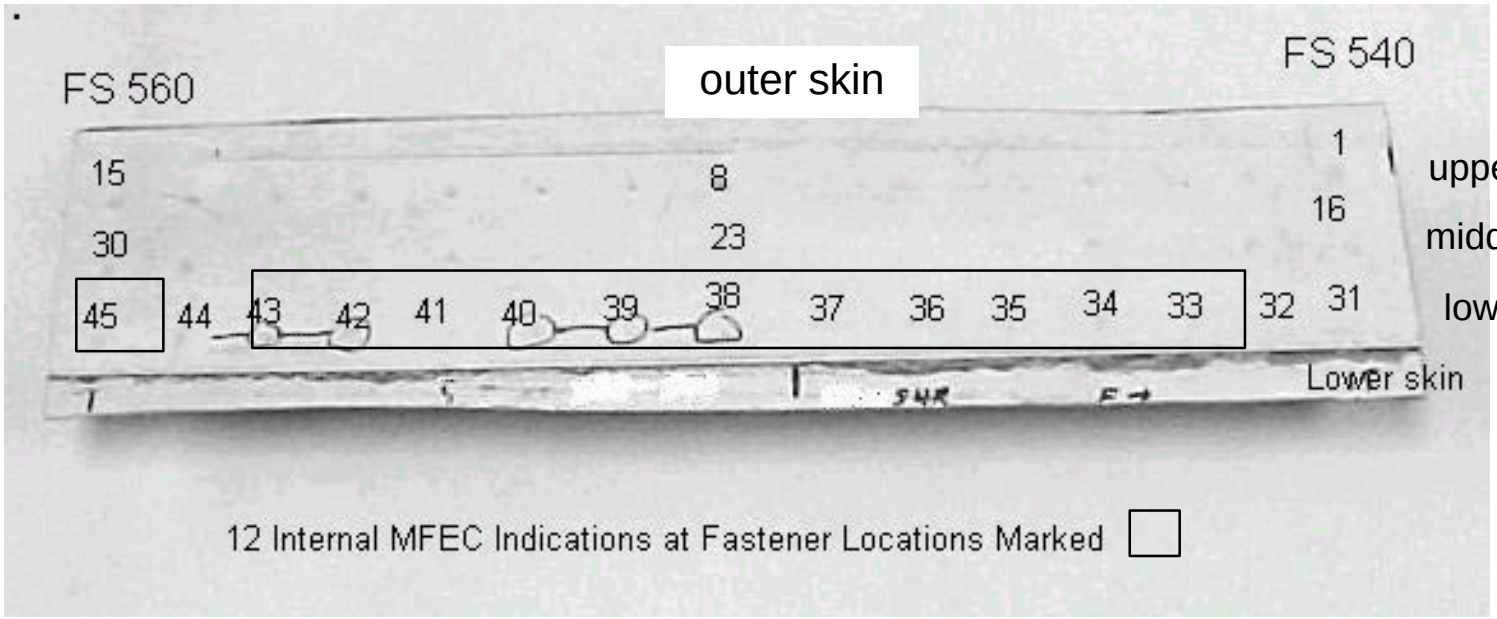
This was done for all 45 fasteners in lap joint at stringer 4R and bay FS 540 - 560, and 15 lower row fasteners in the bays at FS 520 - 540 and FS 580 - 600 and representative photographs/stereomicrographs are presented here.

In order to present the results at a specific location on the joint, the result was assigned a location code in a manner that would be easily identifiable, unique and consistent across the different studies being carried out by the team. An example code is:

540+05.7~4R+1.0~LSH~ crack 3 origin 2 long stria 22



Part 1: Pre-teardown microscopy and measurements



upper row at 4R-1.0

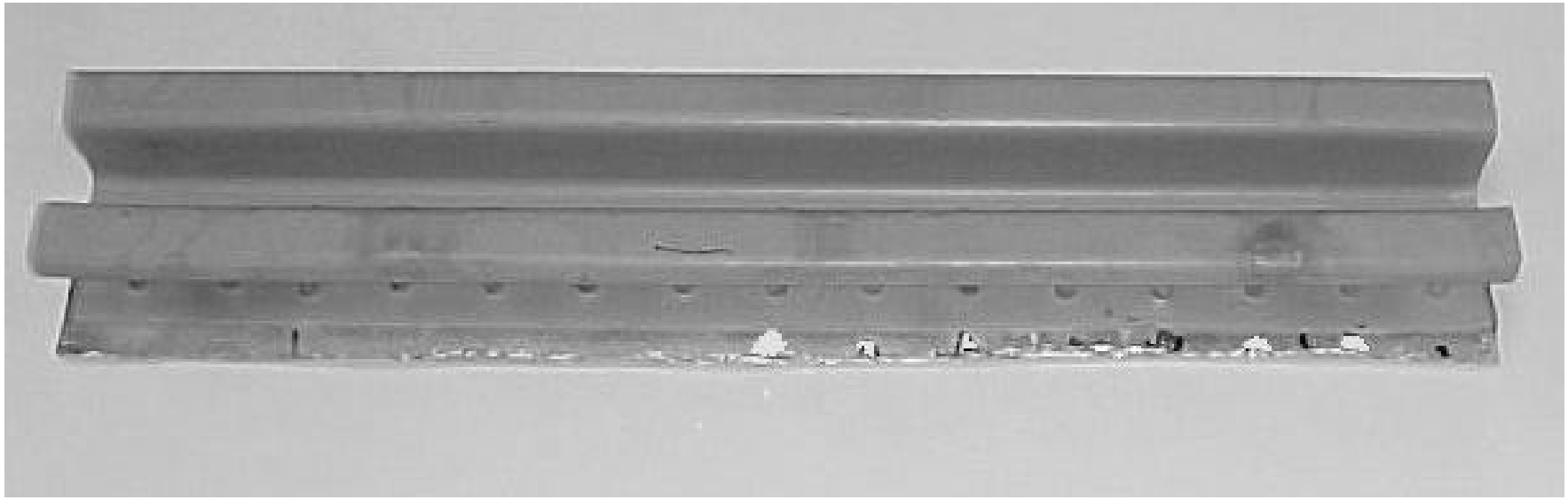
middle row at 4R+0.0

lower row at 4R+1.0

External view of a representative lap joint bay at stringer 4R, FS 540 to 560, cut out from panel F3 for destructive characterization of all fastener holes in the joint.

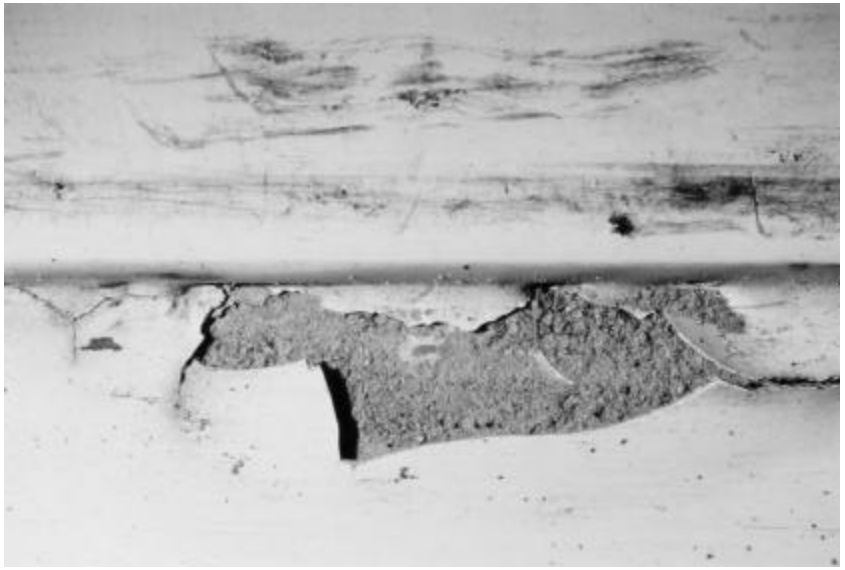
The joint at this and the two other bays (520-540 and 580-600) consists of a 0.060” thick bonded outer skin (0.040+0.020) of Al-clad 2024-T3, on top of a 0.040” thick lower skin also of Al-clad 2024-T3, with BACR15CE-D rivets. The rivets were installed per Boeing process specification BAC 5004 and drawing 69-63000, sheet 1.

Part 1: Pre-teardown microscopy and measurements



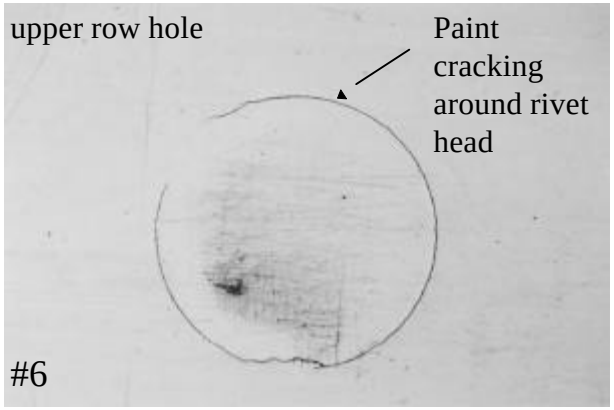
Lap joint bay at stringer 4R , FS 540 to 560, cut out from panel F3 for destructive characterization of all fastener holes in the joint. View looking outboard.

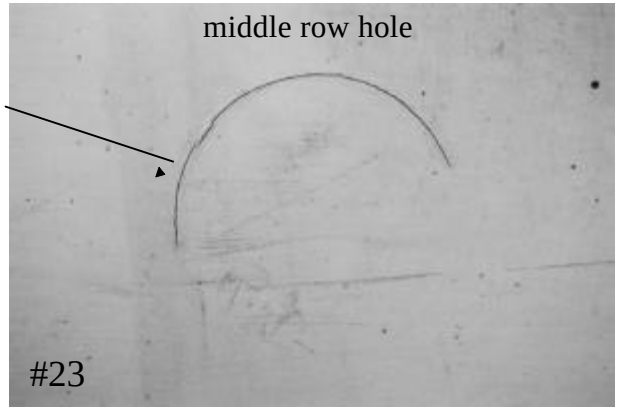
Part 1: Pre-teardown microscopy and measurements

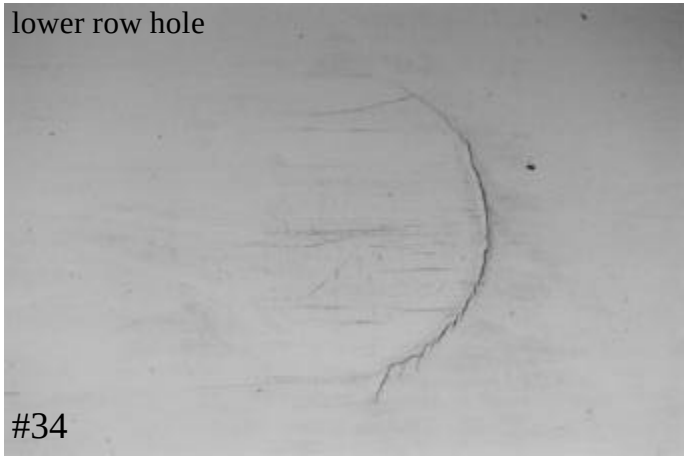


Documentation of the joint condition showing cracked and peeled paint along the line where the upper skin overlaps the lower skin. Though protection afforded by the paint was lost, general corrosion was not observed; the gritty appearance of the surface inside the area where the paint is peeled off is due to adhered sand particles.

Part 1: Pre-teardown microscopy and measurements

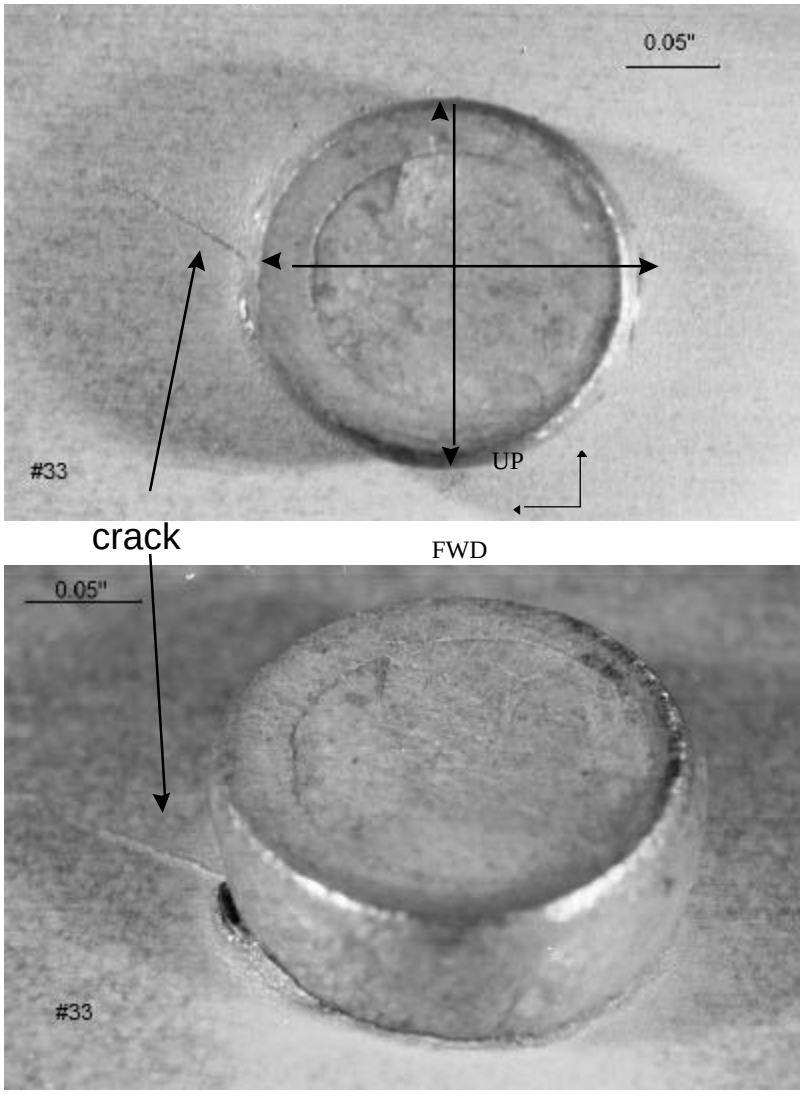






Representative documentation of the exterior views of rivets in the outer skin, one from each of the three rows in the lap joint bay at 4R FS 540-560, showing cracking of the paint around the countersunk head. This was observed to varying extents on every fastener in this bay and other bays. All of the rivet heads appeared to be flush in the countersinks and there were no abnormal installations observed.

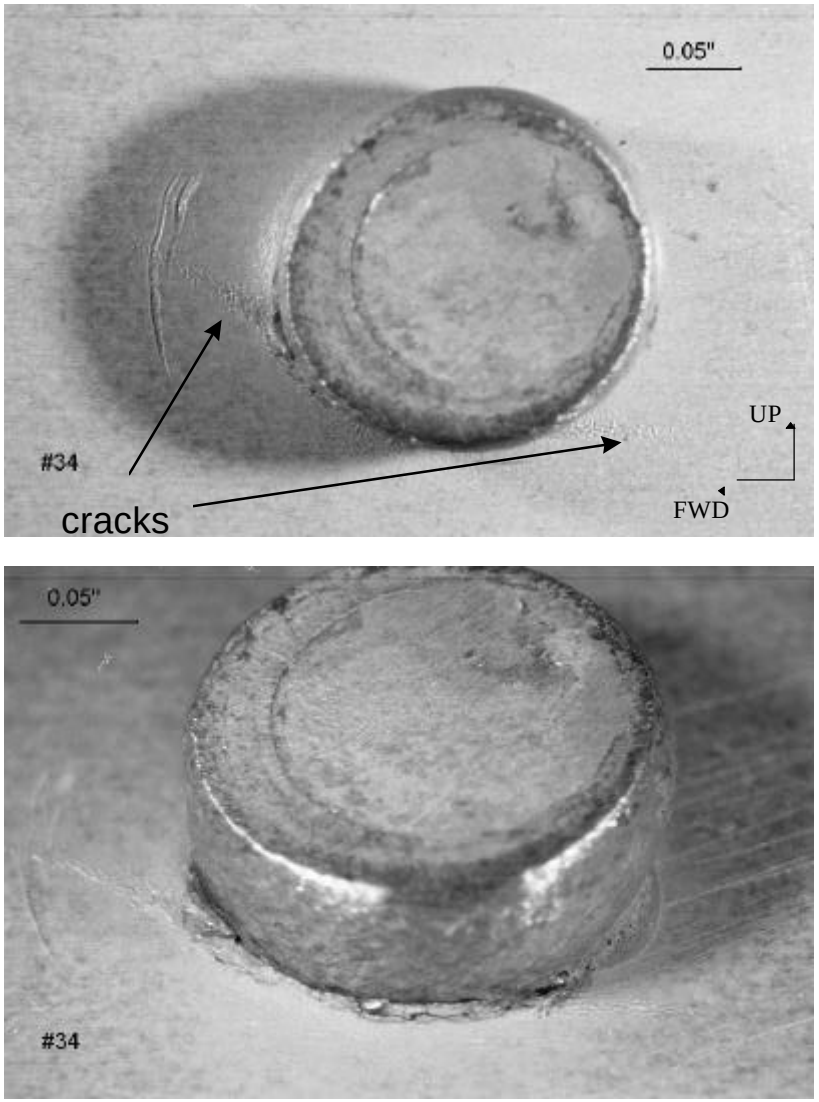
Part 1: Pre-teardown microscopy and measurements



rivet bucked tail diameters were measured in the fwd-aft and up-down directions and the tilt direction noted

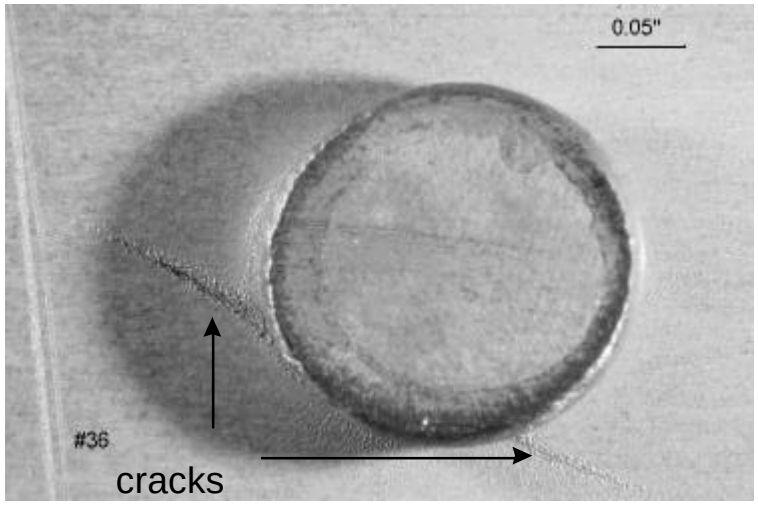
Normal and tilted (40^0) views of lower skin around cracked rivet hole # 33 – lower row in lap joint. The tilted view is of the lower segment of the rivet.

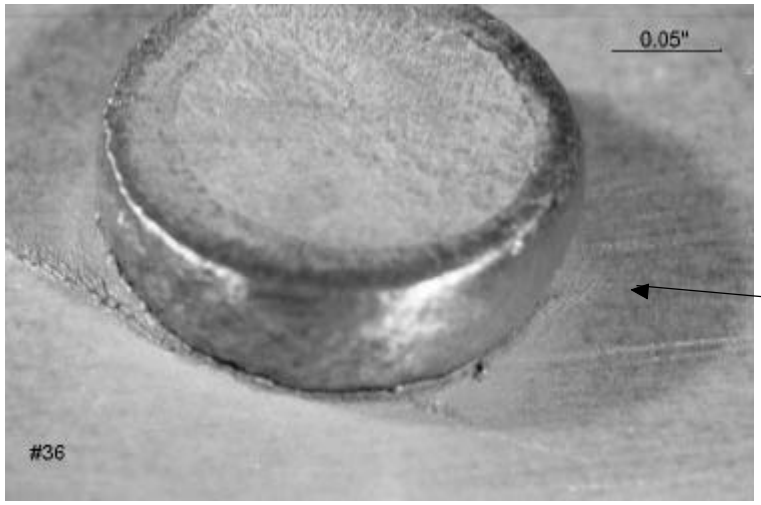
Part 1: Pre-teardown microscopy and measurements



Representative documentation: Normal and tilted (40^0) views of lower skin around cracked rivet hole # 34 in lower row of lap joint bay. The tilted view is of the lower segment of the rivet.

Part 1: Pre-teardown microscopy and measurements





UP

FWD

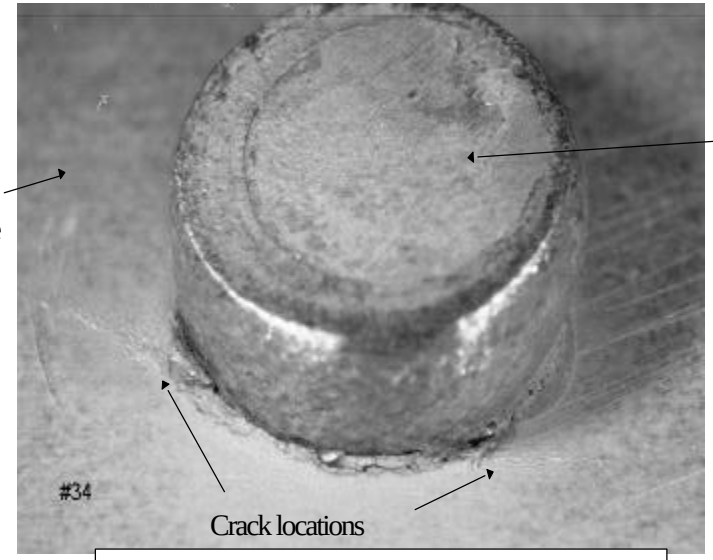
Additional crack seen under rivet tail in tilted view of the lower segment of rivet hole

Representative documentation: Normal and tilted (40^0) views of lower skin around cracked rivet hole # 36 in lower row of lap joint bay. The tilted view is of the lower segment of the rivet and shows an additional crack that is hidden under the rivet tail and not seen in the normal view in top photograph.

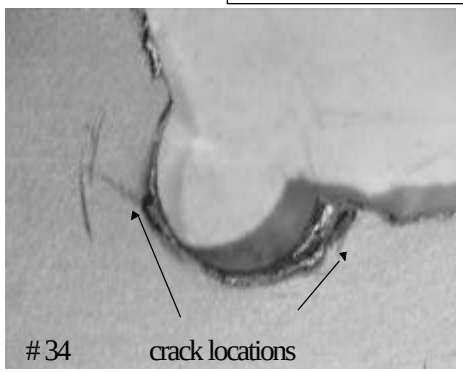
Part 1: Teardown Methodology

- Following initial documentation/measurements, the lap joint dis-assembly followed:
  - Each fastener hole in the joint was cut out in the form of ~1” square coupons;
  - The rivets were removed by making two cuts from the edge of the coupon to the hole; the cut locations were selected based on the initial stereomicroscope inspection of the fastener hole so as to retain “interesting” features and not destroy them in the teardown process;
  - Selected rivet hole interiors were documented under a stereomicroscope;
  - Each of the cut coupons were then soaked in a solvent (d-Limonene/carboxylate ester) which softened the sealant between the joint, and facilitated separating the outer and lower skins;
  - Documentation of the faying surface(s) and crack(s) was done with a stereomicroscope;
  - The cracks were then broken open after an initial saw cut was made to within 0.050” of the observed crack tip and the coupon cooled in LN2;
  - To remove a thin layer of smut and corrosion products which obscured the crack surface during SEM viewing, the sections containing the cracks were ultrasonically cleaned in a dilute solution of Liquid SMUT-GO, distilled water and finally rinsed with isopropyl alcohol

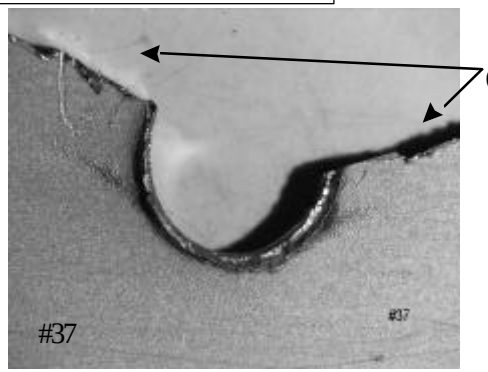
Part 1: Teardown Methodology



Hole #34 prior to removing rivet showing visible crack locations



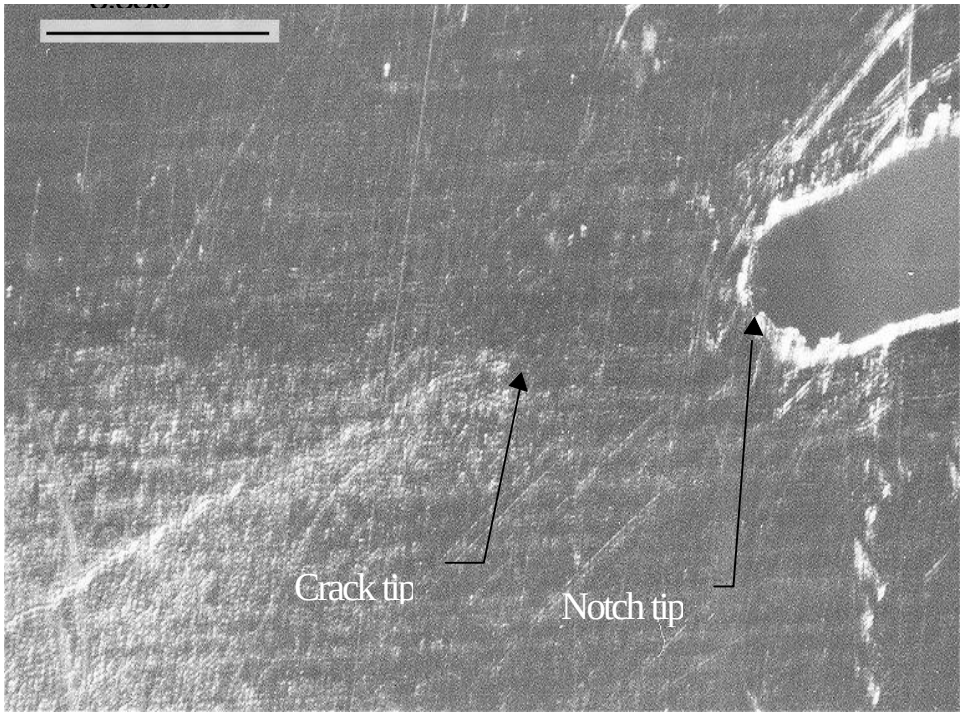
Hole #34 after rivet removal;



cuts in skins to remove the rivet

Another example: Hole #37 after rivet removal

Part 1: Teardown Methodology

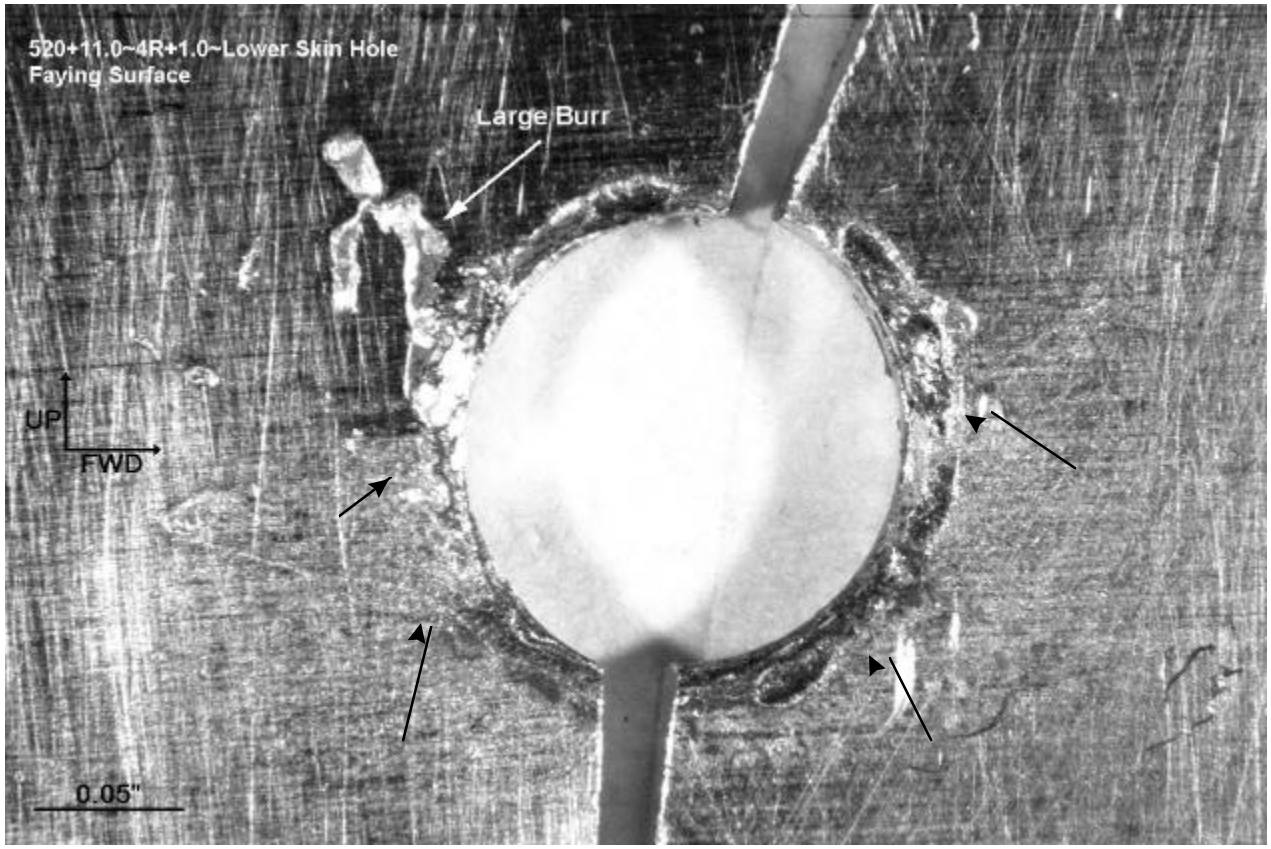


Photograph showing slitting wheel cut in the lower skin up to about 0.05" from the edge of the crack in hole #34 seen in Figure 9. Note that the crack orientation is reversed as this view is of the crack in faying surface while in Figure 9, the view is of the inboard surface of the lower skin. The ligament between the crack and the slot is easily broken after the sample is cooled in liquid nitrogen, in order to expose the crack for fractographic analysis.

Part 1: Representative Stereomicroscopy Results After Teardown

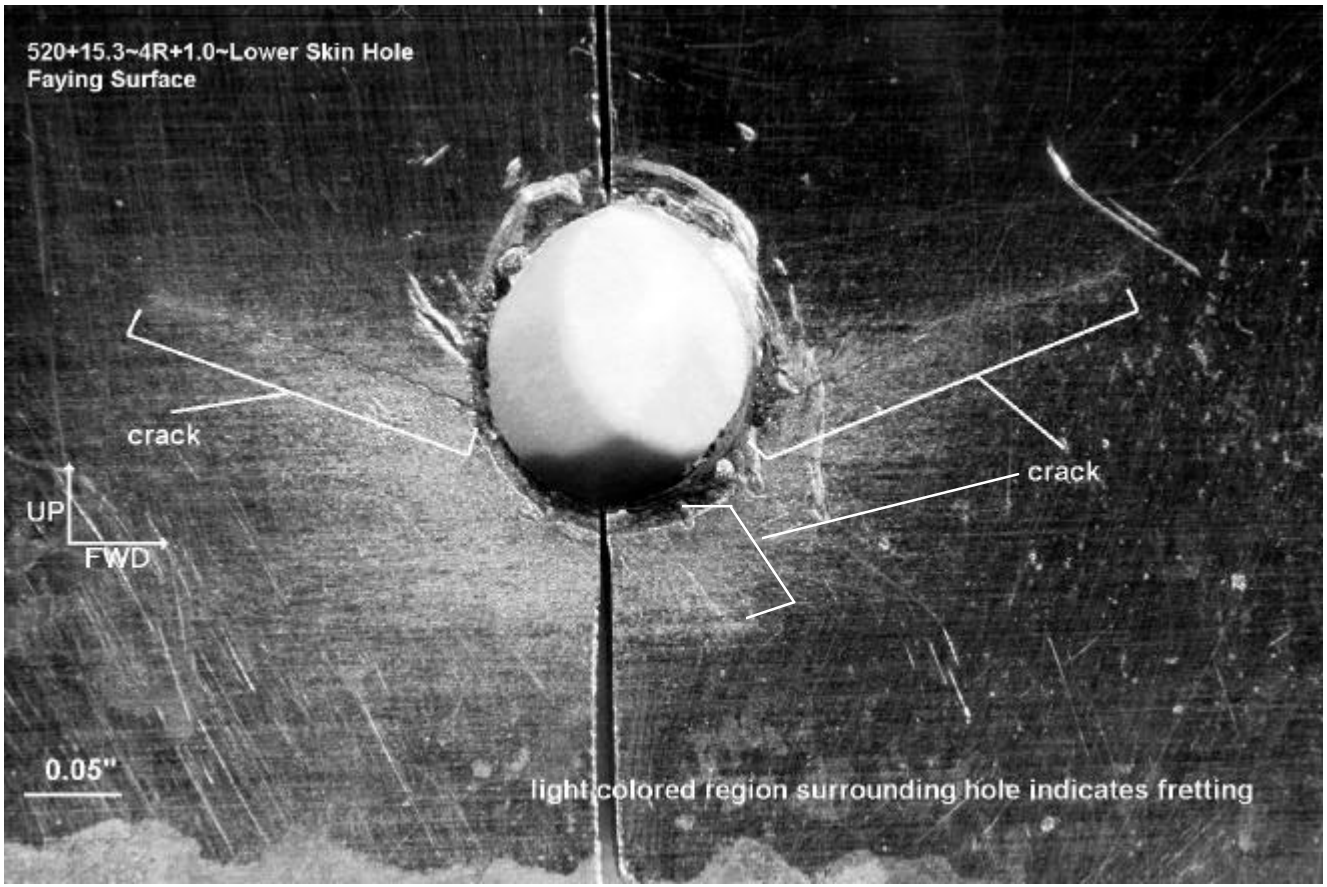
- Lower skin faying surface at hole location 520+11.0~4R+1.0~LSH

Note the presence of 4 cracks and fretted, gouged regions around the hole edge through which the cracks pass



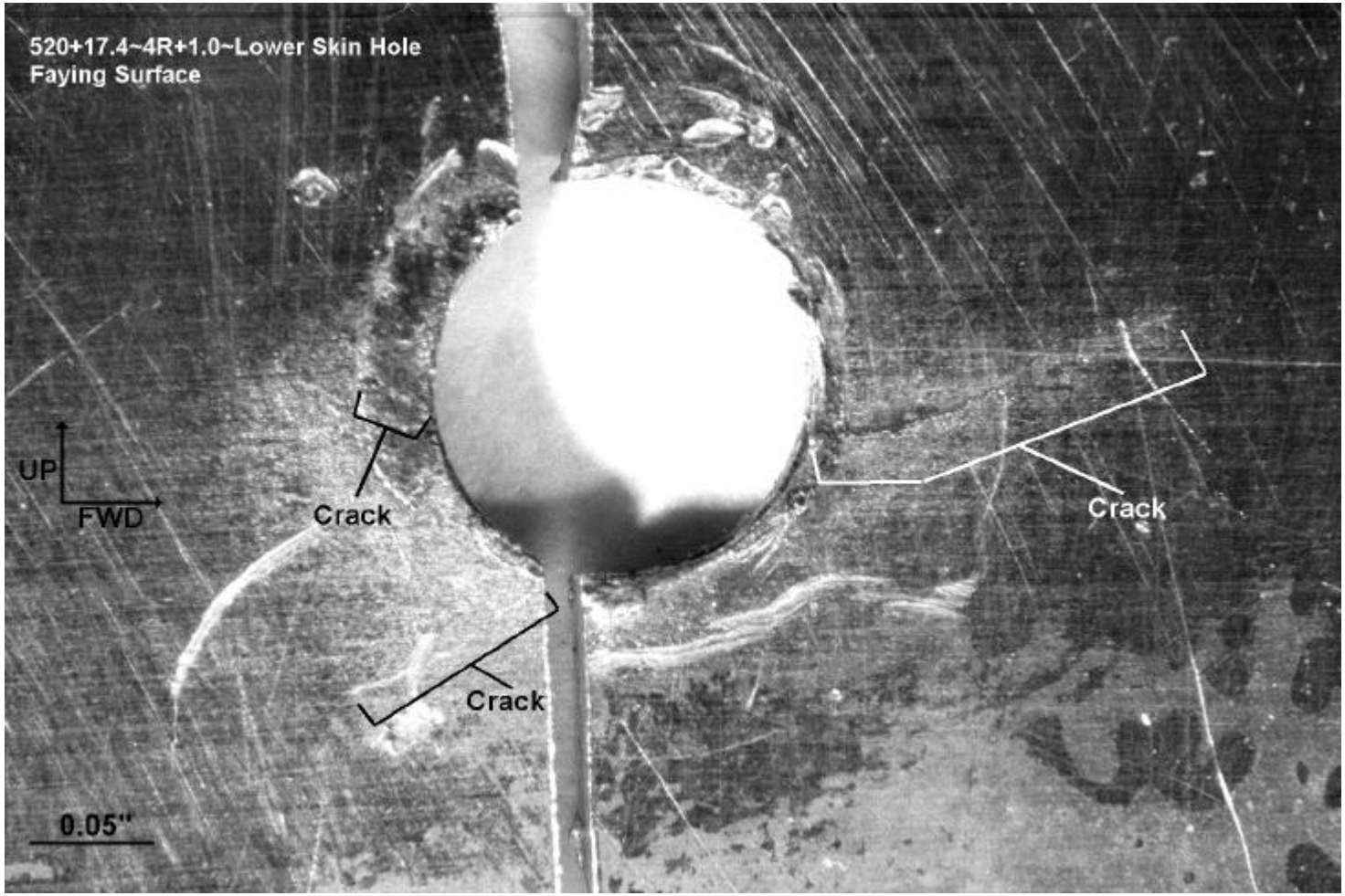
Part 1: Representative Stereomicroscopy Results After Teardown

- Lower skin faying surface at hole location 520+15.3~4R+1.0~LSH



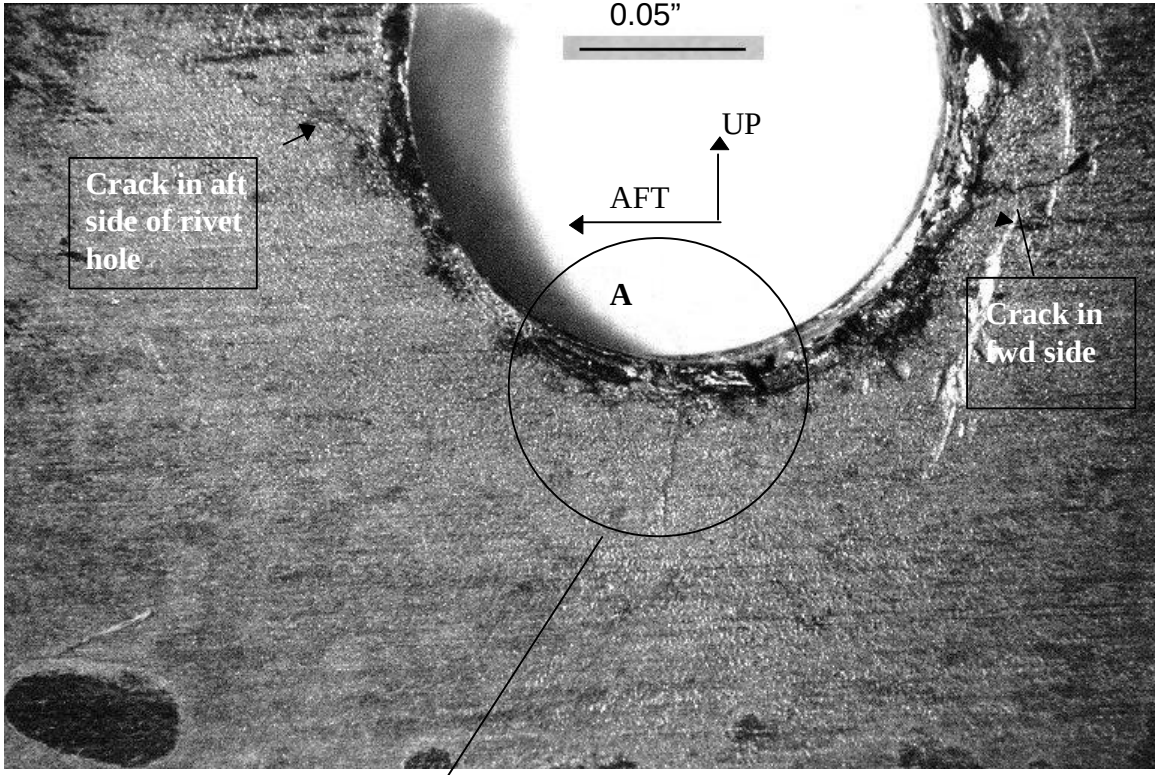
Part 1: Representative Stereomicroscopy Results After Teardown

- Lower skin faying surface at hole location 520+17.4~4R+1.0~LSH



Part 1: Representative Stereomicroscopy Results After Teardown

- Lower skin faying surface at hole location 540+06.8~4R+1.0~LSH

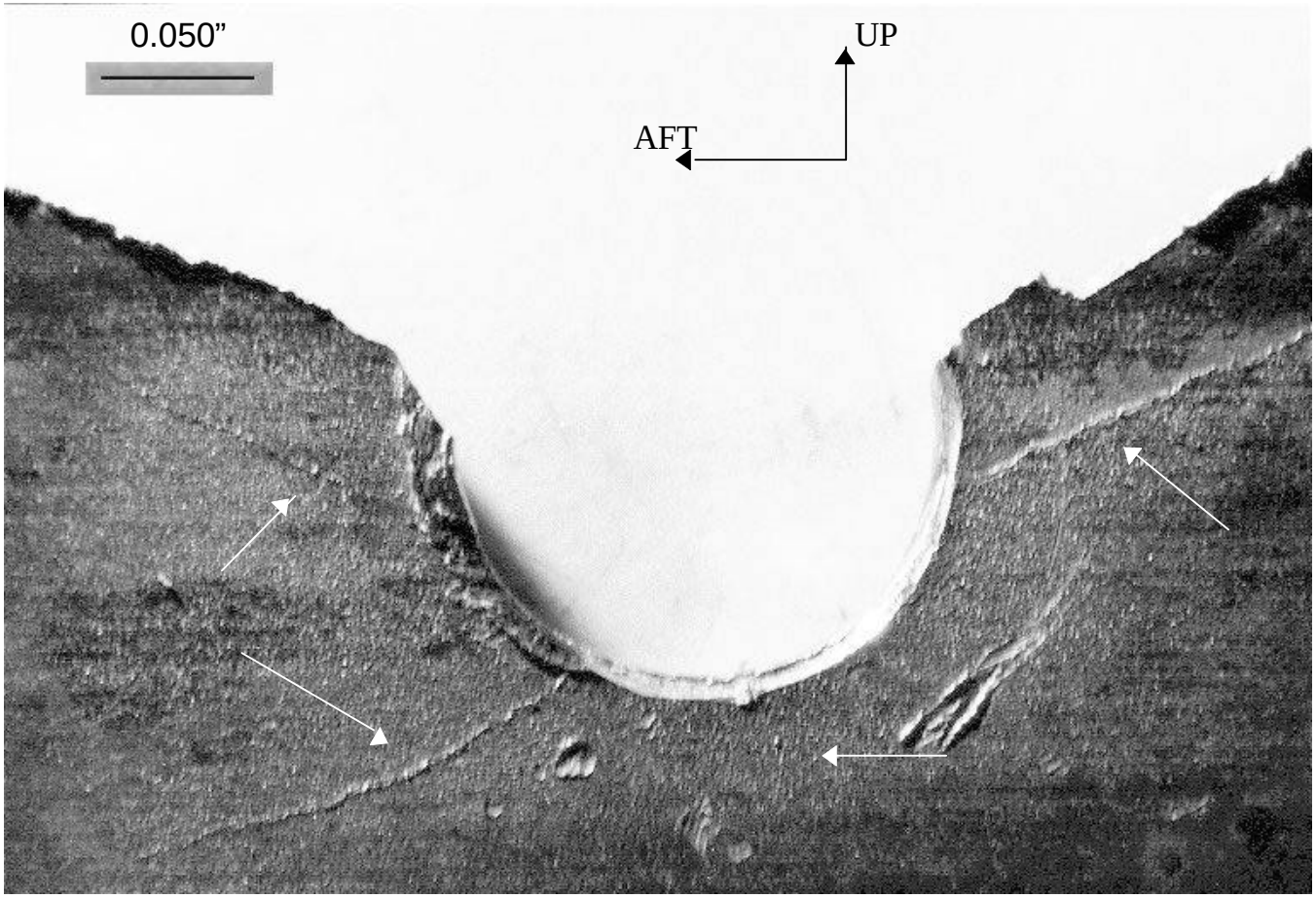


Note the regions of fretting and gouges/tool marks seen near the cracks

In addition to the two main cracks seen forward and aft of the rivet hole, there are at least 3 more cracks in this region running radially away from the hole.

Part 1: Representative Stereomicroscopy Results After Teardown

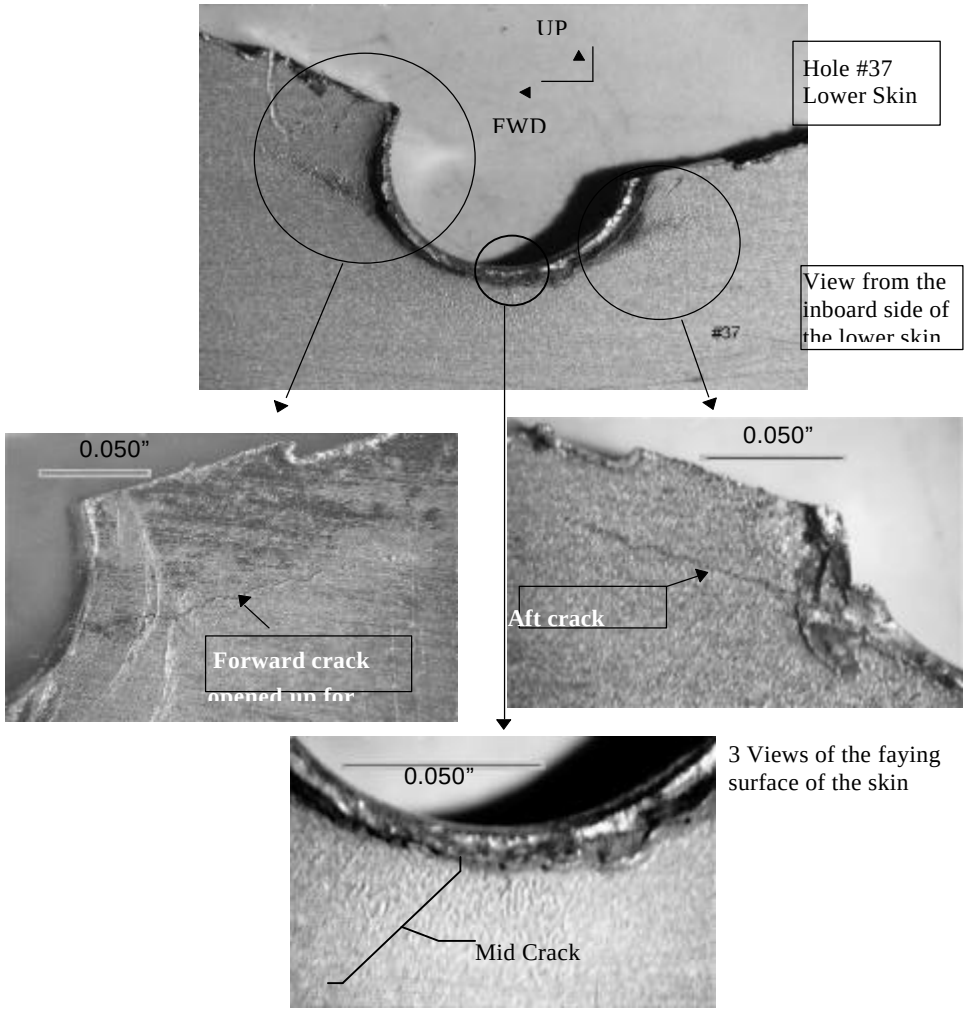
- Lower skin faying surface at hole location 540+07.9~4R+1.0~LSH



Faying surface of lower skin showing four cracks emanating from the hole as identified by arrows.

Part 1: Representative Stereomicroscopy Results After Teardown

- Lower skin faying surface at hole location 540+08.9~4R+1.0~LSH

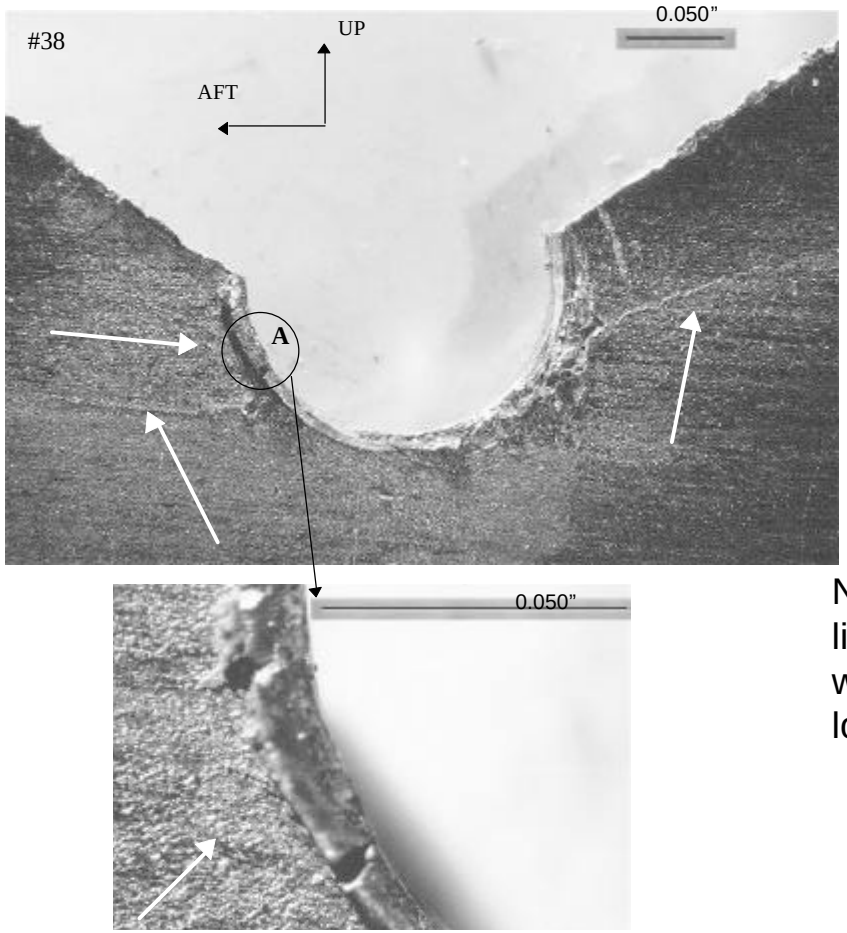


3 Views of the faying surface of the skin

Note the gouged/ deformed regions at the hole edges through which the cracks pass

Part 1: Representative Stereomicroscopy Results After Teardown

Lower skin faying surface at hole location 540+10.0~4R+1.0~LSH



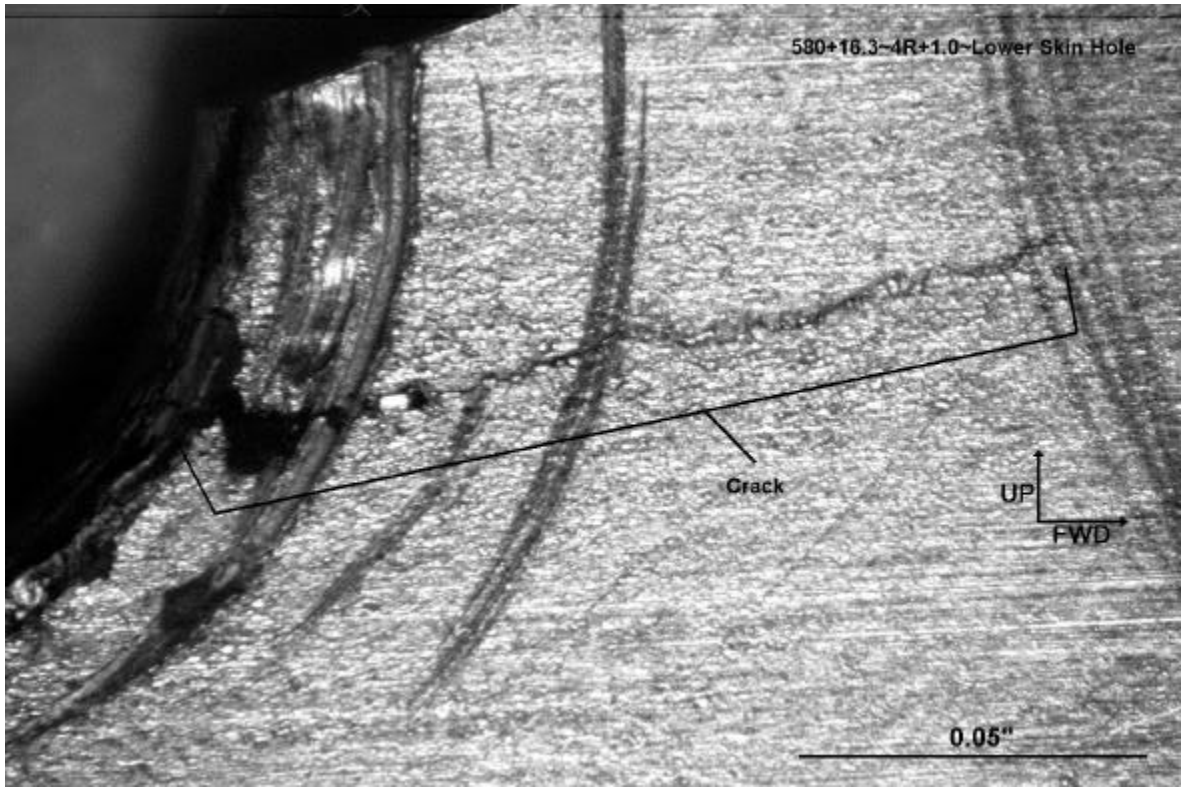
Note the deformed lip at the hole edge where the cracks are located

Part 1: Representative Stereomicroscopy Results After Teardown

- Lower skin faying surface at hole location 580+16.3~4R+1.0~LSH

Note the deep gouges/tool marks through which the crack traverses.

Two more cracks were present at this hole but did not show up clearly in the micrographs

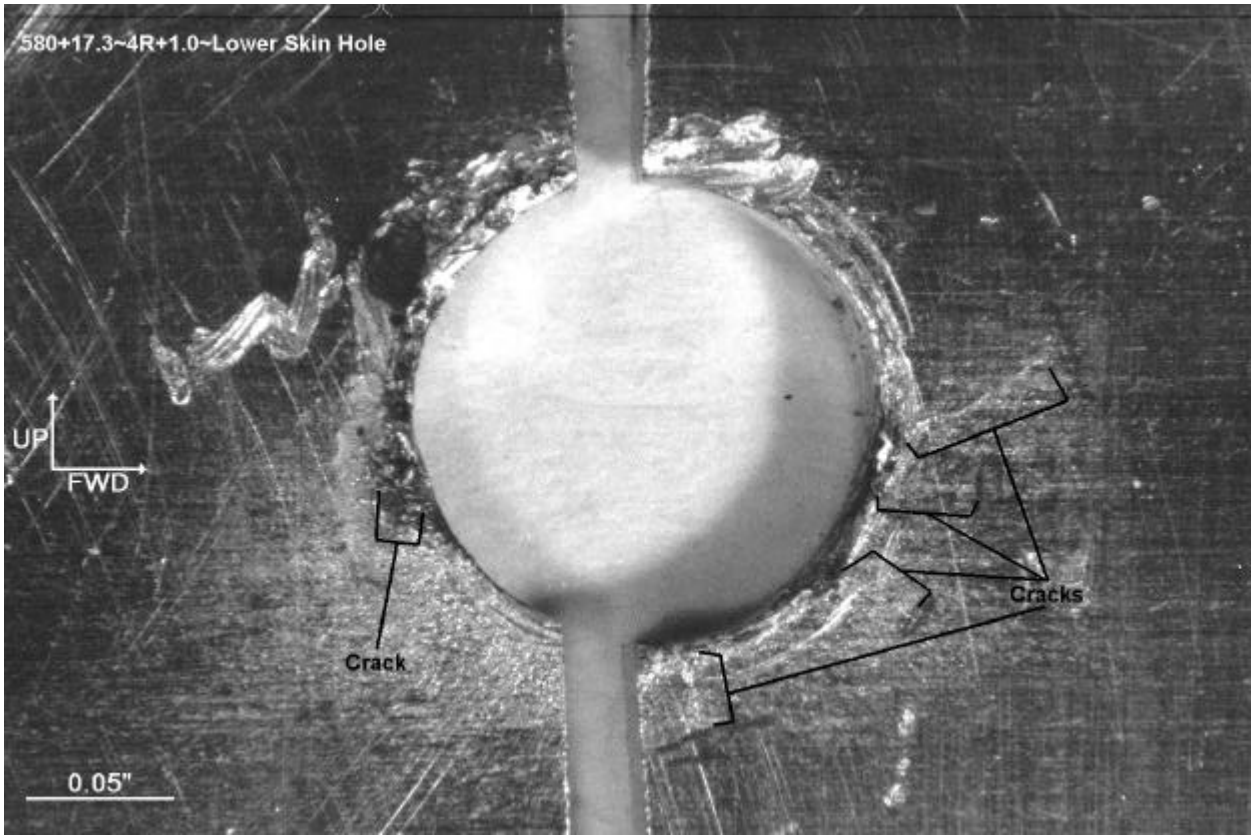


Part 1: Representative Stereomicroscopy Results After Teardown

- Lower skin faying surface at hole location 580+17.3~4R+1.0~LSH

Note the deep gouges/tool marks present around the hole.

Five cracks were present at this hole as shown



Part 1: Summary of Key Results After Stereo-microscope examination of 3 lap joint bay lower row holes

- Of the 45 lower row holes examined in the three lap joint bays at Stringer 4R, FS 520-540, 540-560 and 580-600, 32 holes were found with cracks in the lower skin;
- Outer skin cracking was not detected in the stereomicroscope examination;
- Of the 32 holes with cracks, at least 14 holes had more than two cracks present in the lower skin;
- Where more than two cracks were present, some of the cracks were aligned in the fuselage circumferential direction;
- All the cracks detected were present in the lower two quadrants of the hole;
- The faying surface of the lower skin, particularly near hole edges, was gouged/scored and deformed; fretting was evident in some areas around the holes; debris (metal drill shavings which had not broken off) was also present on the surface at some of the holes.

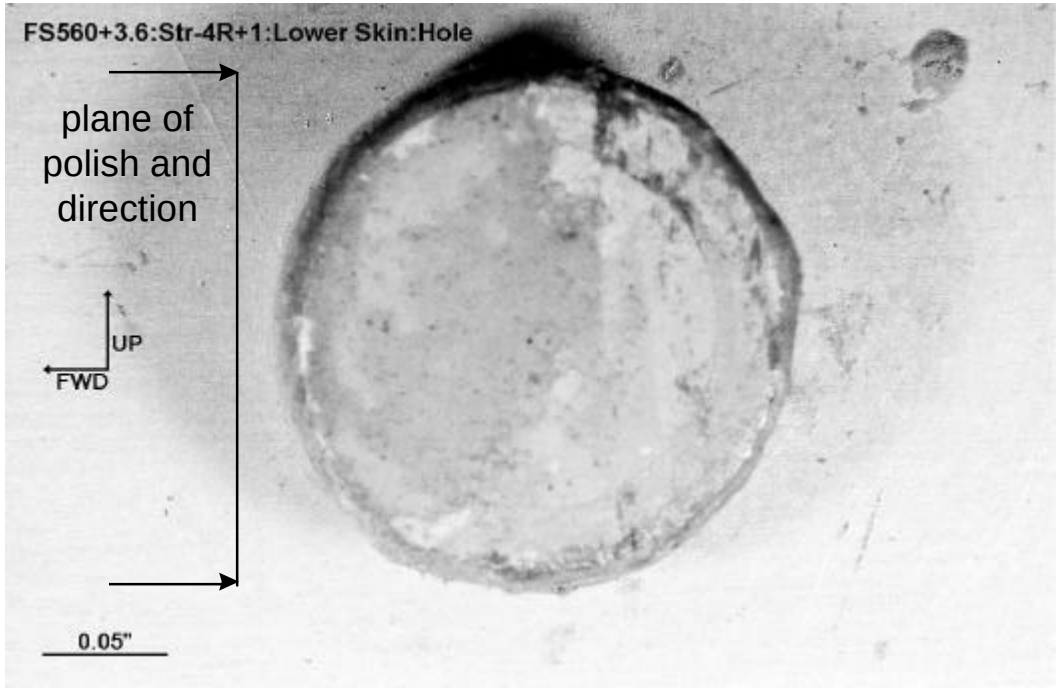
Part 2: Rivet Installation and Hole Quality Studies

The presence of more than two cracks in a large number of holes coupled with their circumferential orientation suggested local stresses around the hole possibly from the riveting process.

This lead to the study of the riveting process through progressively sectioning representative lap joint coupons with the rivet still installed, after mounting them in Bakelite and polishing down until the hole/rivet center was revealed. The three representative lap joint coupons were taken from from bay 4R, FS 560-580, which had not been dis-assembled fully.

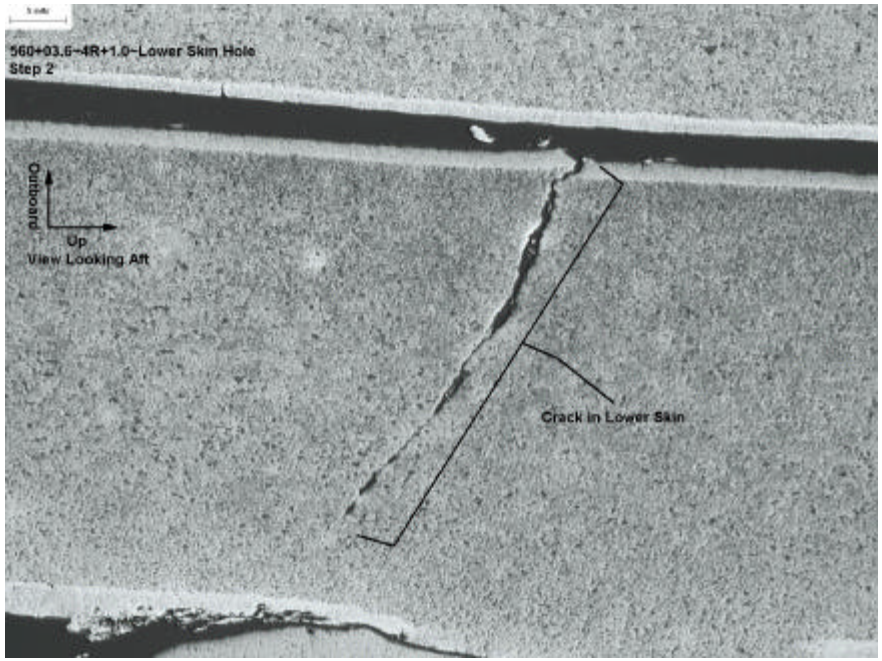
Part 2: Rivet Installation and Hole Quality Studies

- Normal view of a lap joint lower row hole coupon with a rivet still installed. The hole is at location 560+3.6~4R+1. This coupon was polished down in the direction shown with the plane of polish as defined.



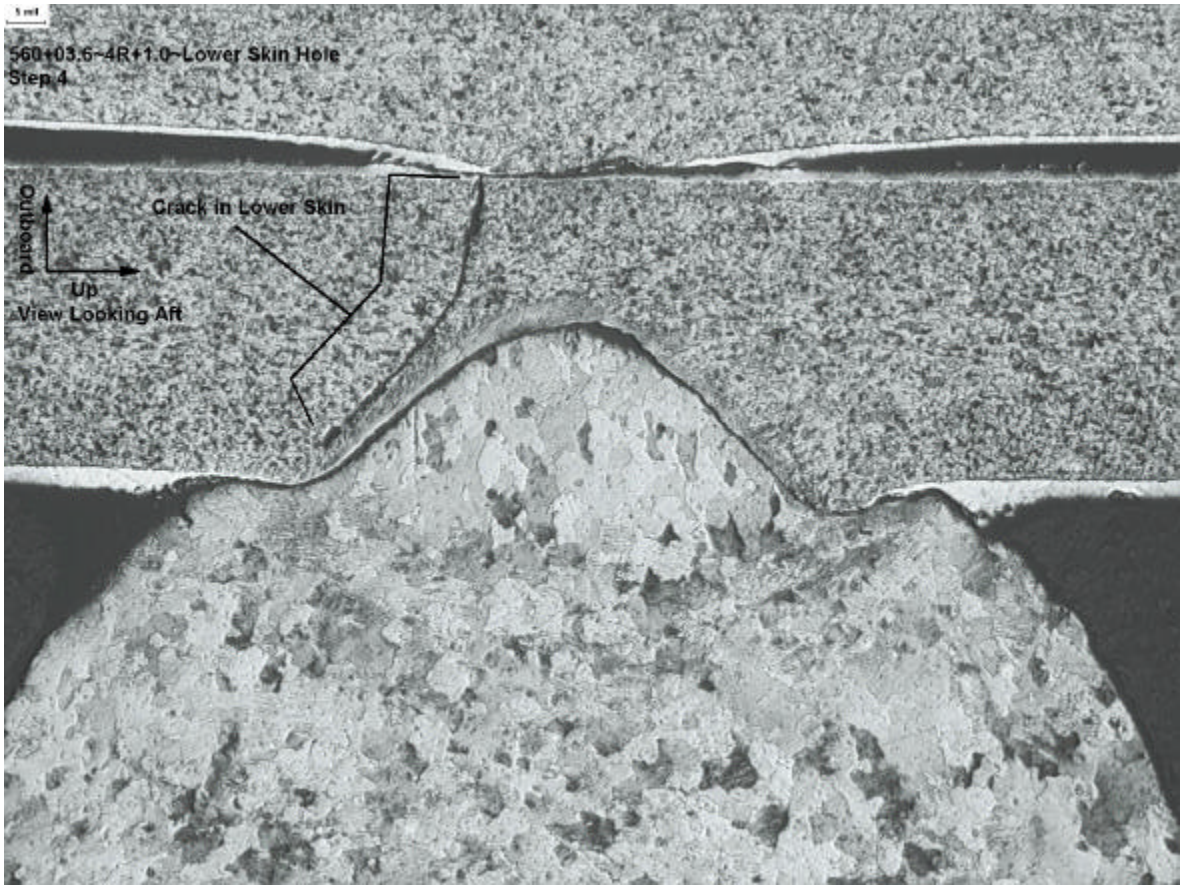
Part 2: Rivet Installation and Hole Quality Studies

Cross sectional view of the lap joint coupon 560+3.6~4R+1 after initial sectioning and polishing. Note the presence of a crack in the lower skin which was not evident on the inboard surface.



Part 2: Rivet Installation and Hole Quality Studies

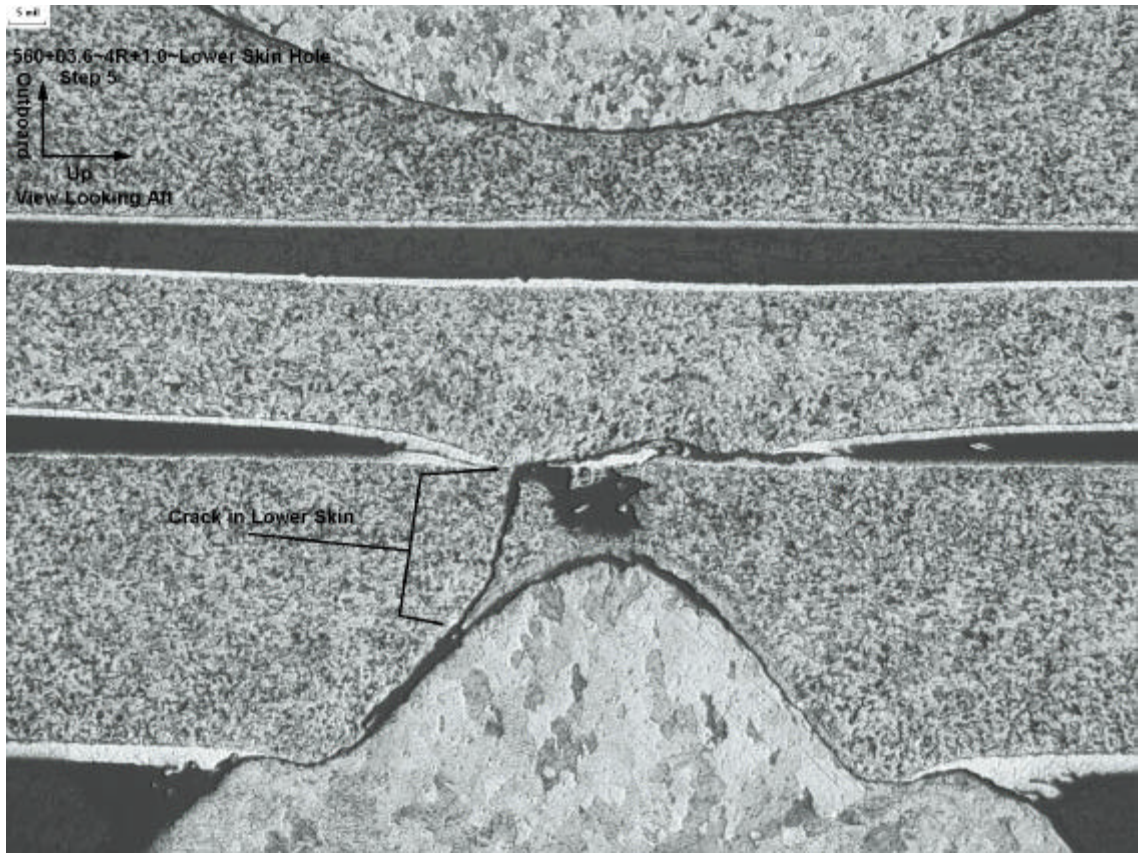
- Cross sectional view of the lap joint coupon 560+3.6~4R+1 after further polishing



Part 2: Rivet Installation and Hole Quality Studies

- Cross sectional view of the lap joint coupon 560+3.6~4R+1 after further polishing

Note the presence trapped debris between the lower and outer skin at the rivet



outer skin 0.040”

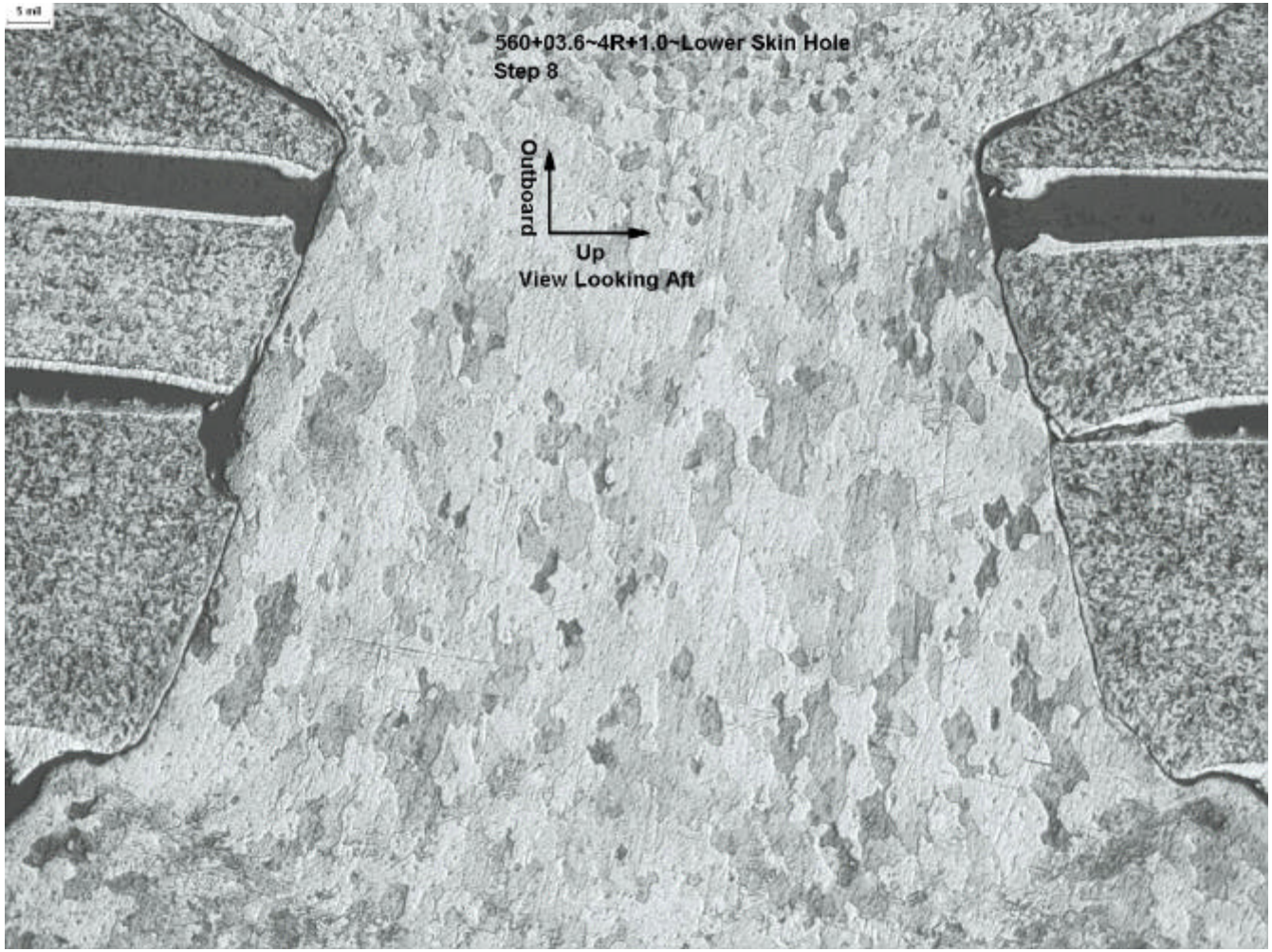
bonded outer skin 0.020”

lower skin 0.040”

rivet bucked tail

Part 2: Rivet Installation and Hole Quality Studies

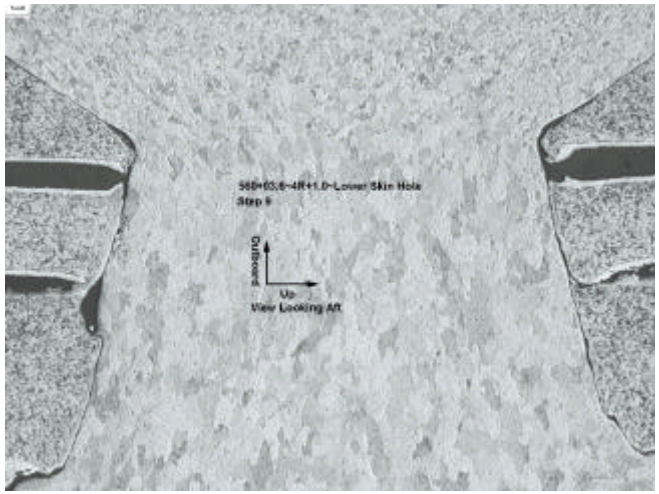
- Cross sectional view of the lap joint coupon 560+3.6~4R+1 after further polishing

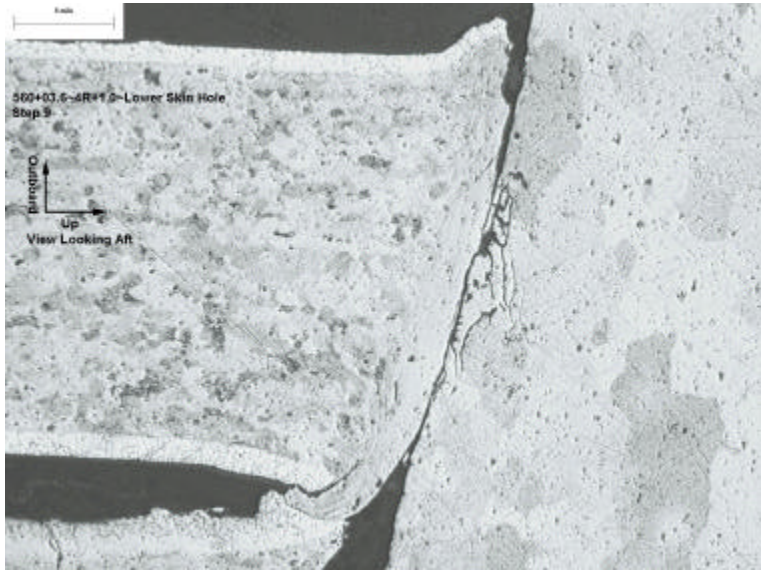


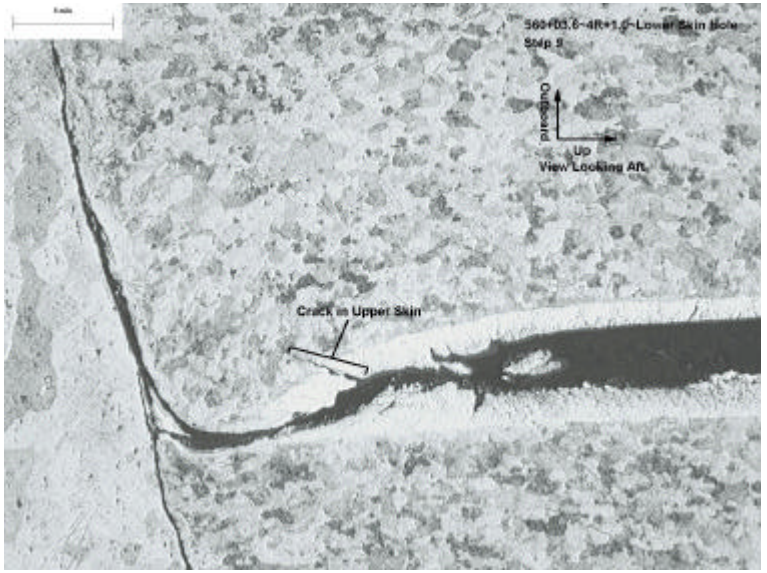
Part 2: Rivet Installation and Hole Quality Studies

- Cross sectional view of the lap joint coupon 560+3.6~4R+1 after further polishing

Note the rivet deformation into groove in the lower skin and lower skin deformation; Note also cracking in the rivet

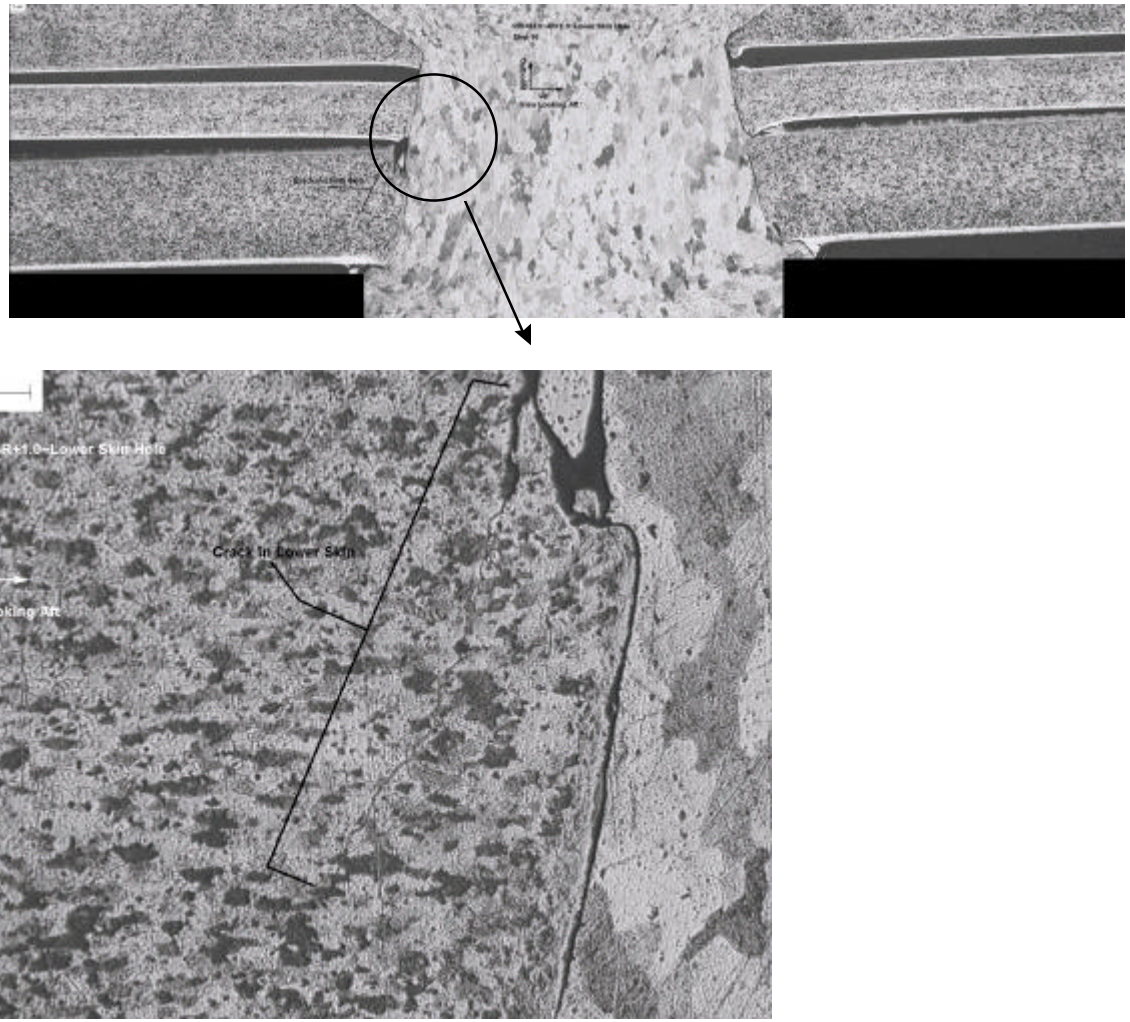






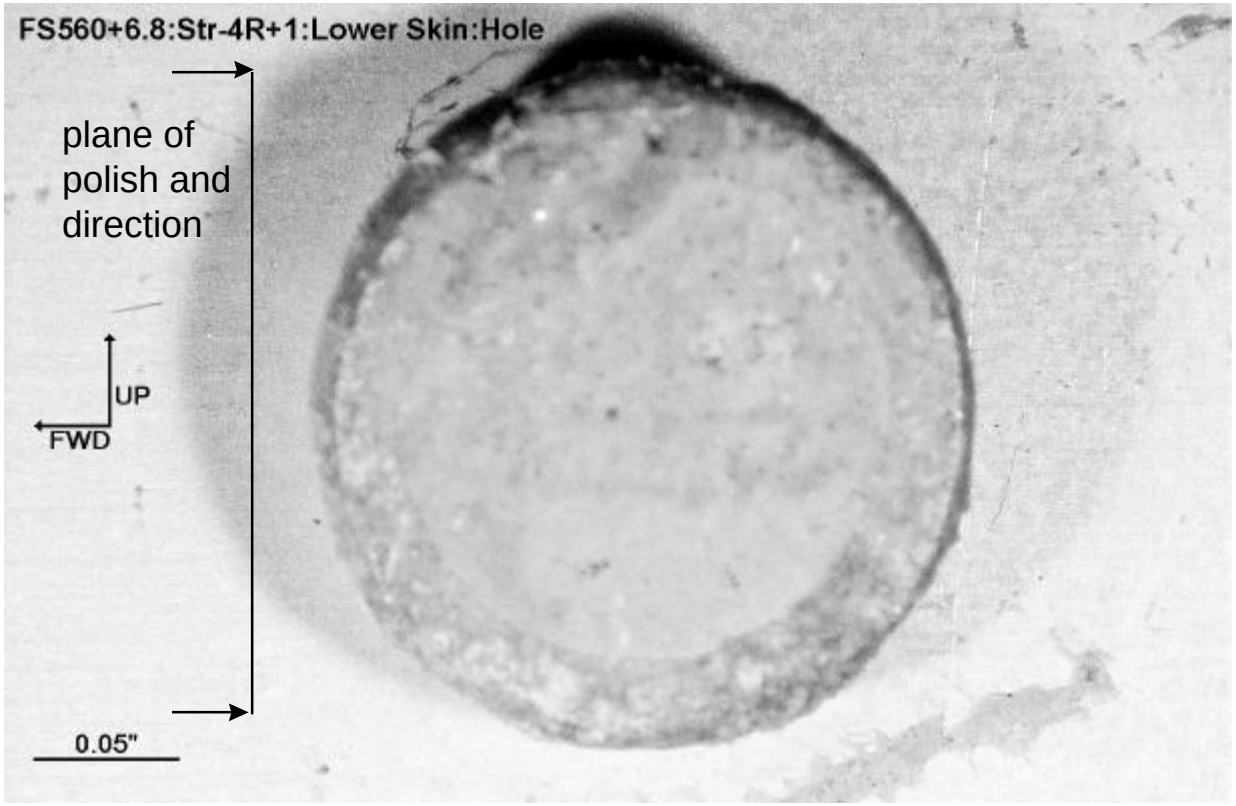
Part 2: Rivet Installation and Hole Quality Studies

- Cross sectional view of polishing down the lap joint coupon 560+3.6~4R+1 - final polishing step



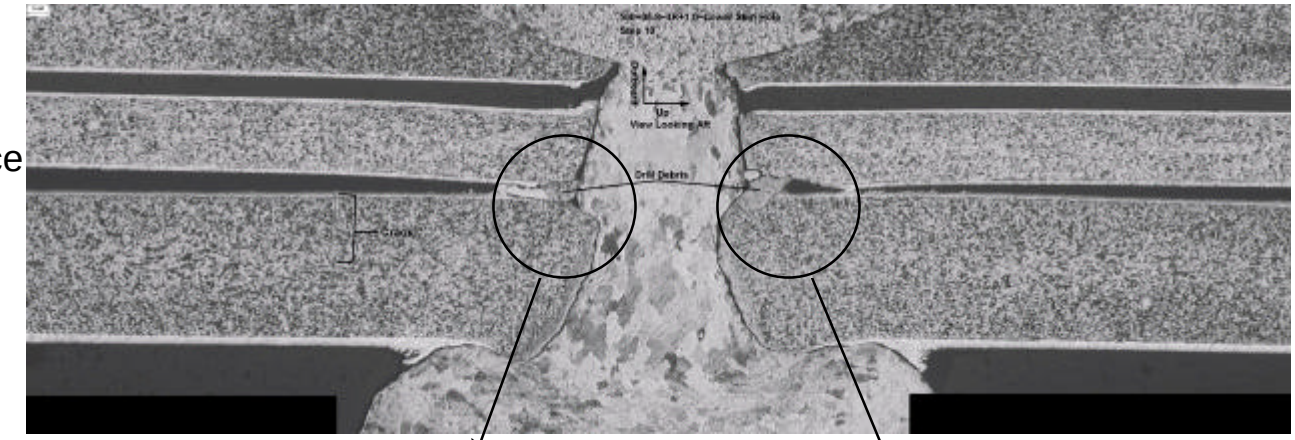
Part 2 : Rivet Installation and Hole Quality Studies

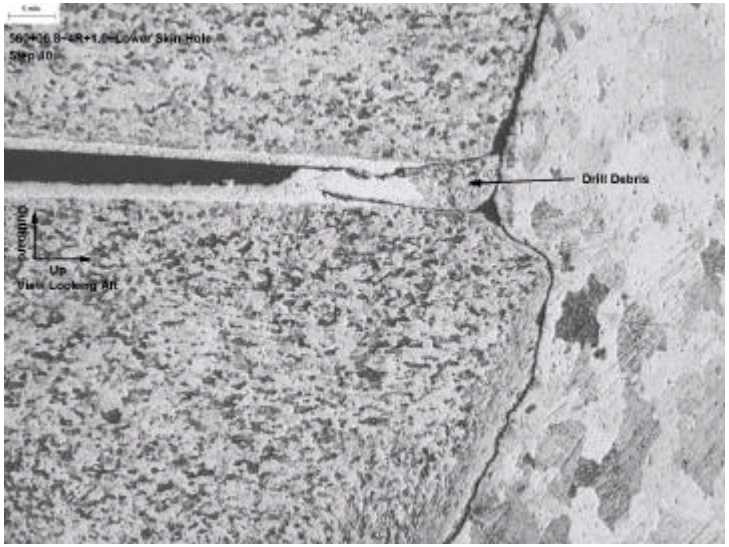
- Normal view of second lap joint coupon at location 560+06.8~4R+1.0 with rivet still installed. This coupon was polished down in the direction shown, with the section plane as defined.

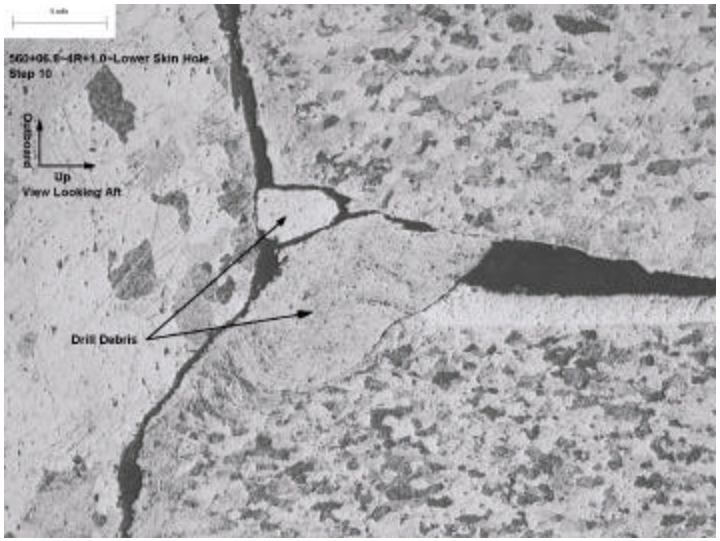


- Cross sectional view of second lap joint coupon at location 560+06.8~4R+1.0 with rivet still installed; view of section through the rivet.

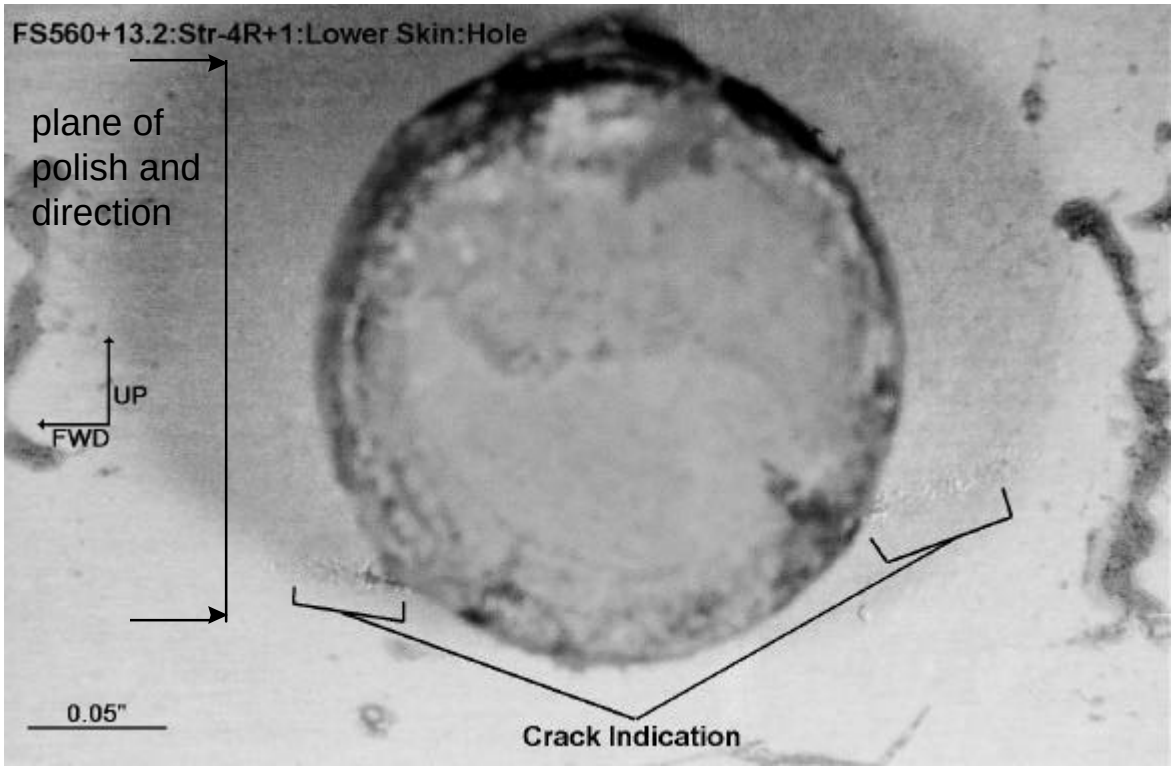
Note rivet deformation into the space below the lower skin pushing the skin outward







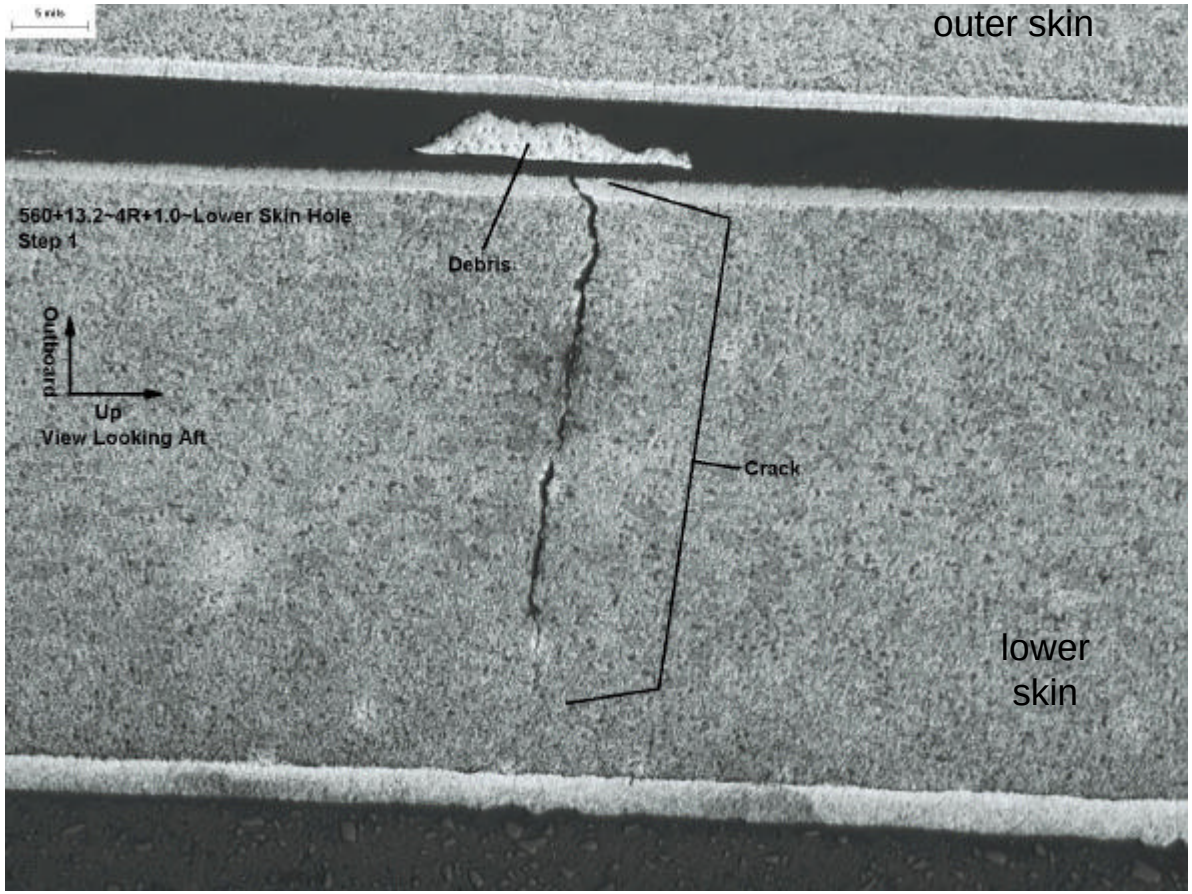
- Normal view of third lap joint coupon at location 560+13.2~4R+1.0~LSH with the rivet still installed. This coupon was polished down as shown, with the section plane as defined.



Part 2: Rivet Installation and Hole Quality Studies

- Sectional view of third lap joint coupon at location 560+13.2~4R+1.0~LSH - initial section outside the rivet showing the crack in the lower skin

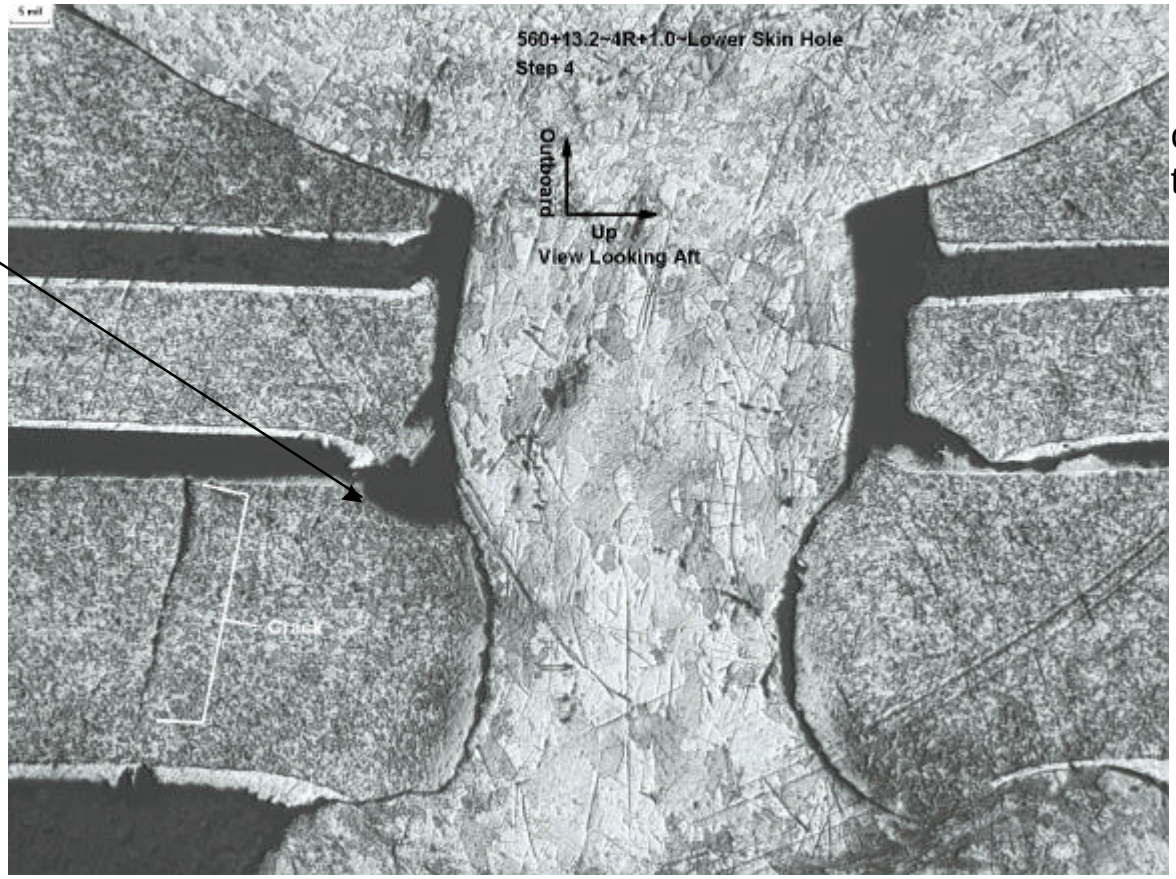
Note the presence of metal debris between the lower and outer skins' faying surfaces and directly above the crack



Part 2: Rivet Installation and Hole Quality Studies

- Sectional view of third lap joint coupon at location 560+13.2~4R+1.0~LSH - intermediate section of the rivet in the joint

Note the groove and the local bending of the lower skin



outer 040" thick skin

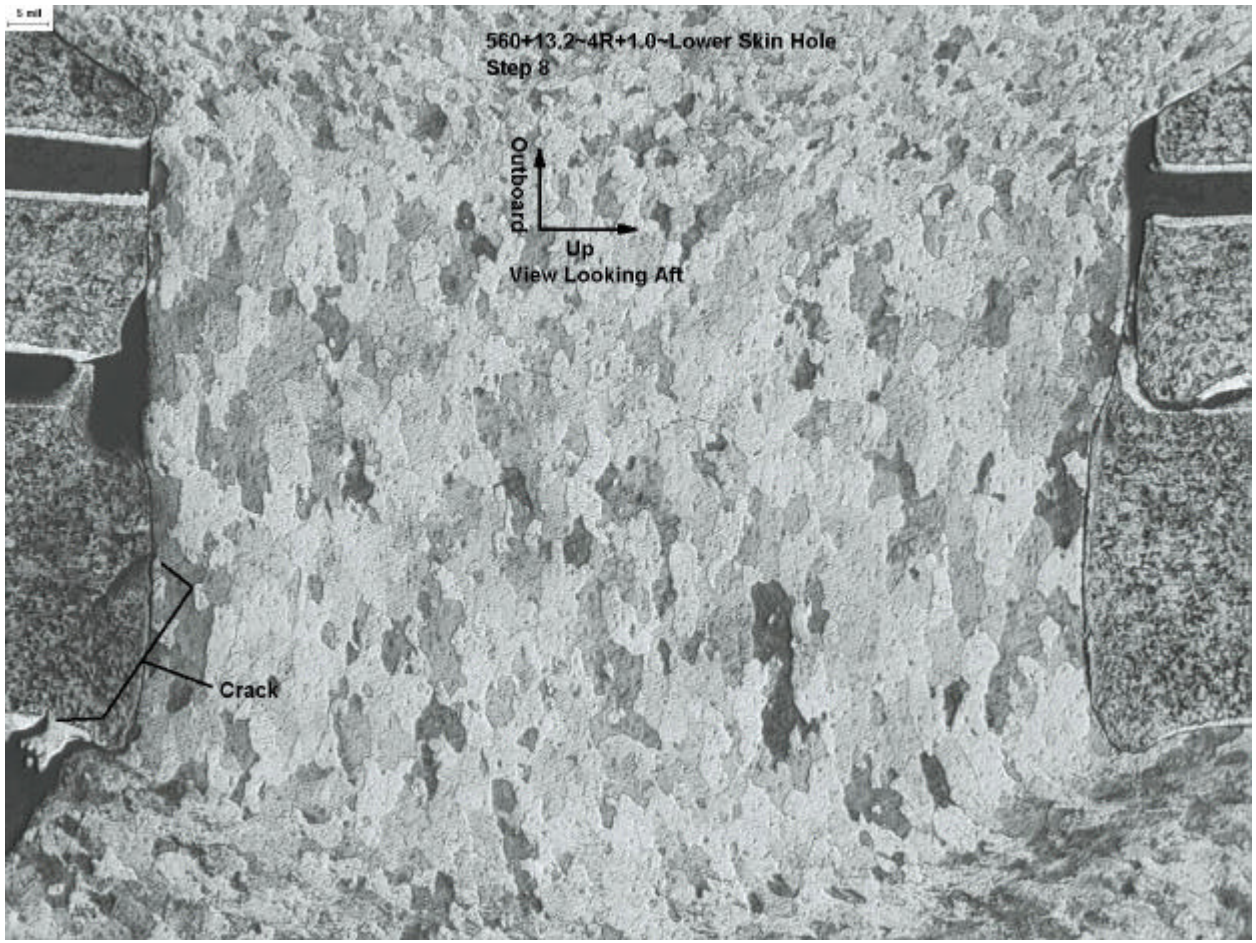
outer bonded 0.020" skin

lower 0.040" skin

rivet bucked tail

Part 2: Rivet Installation and Hole Quality Studies

- Sectional view of third lap joint coupon at location 560+13.2~4R+1.0~LSH - final section of the rivet in the joint

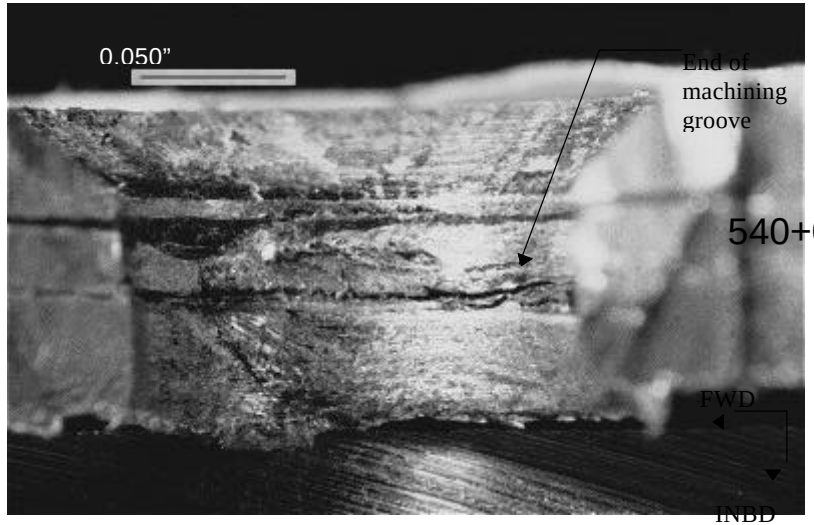


Part 2: Rivet Installation and Hole Quality Studies

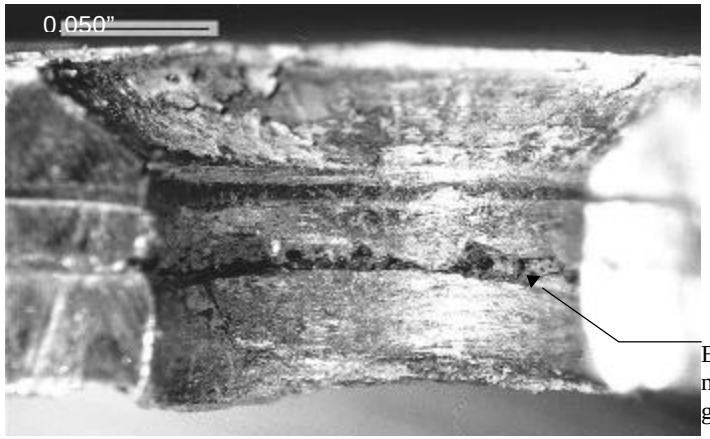
- Representative views of the interior surfaces of two lower row holes at two locations.

Note the end of the spiral groove seen in both holes, in the lower skin at the interface with the outer skin.

This groove corresponds to the cavity seen in the lower skin at the rivet hole in the cross sectional views of the coupons shown previously.



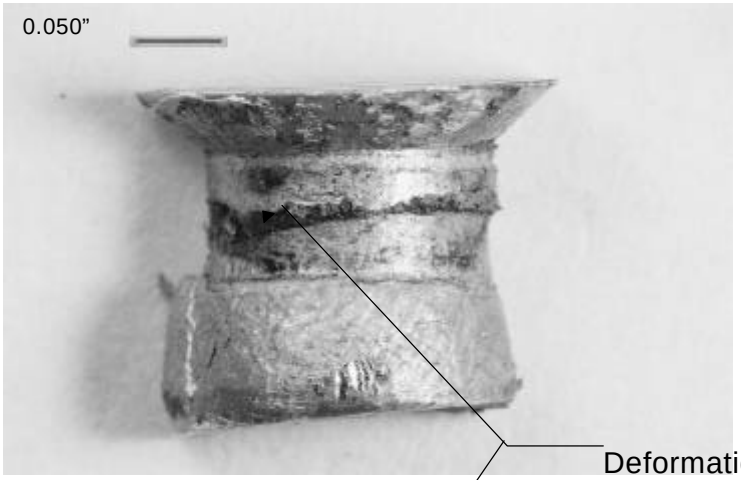
540+05.7~4R+1.0~LSH



540+10.0~4R+1.0~LSH

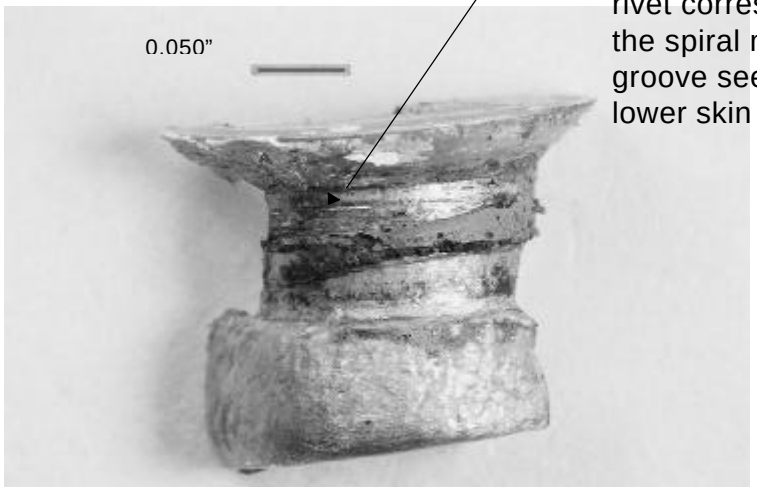
Part 2: Rivet Installation and Hole Quality Studies

- Representative views of rivets from two lower row holes.



540+10.0~4R+1.0~LSH

Deformation seen on rivet corresponding to the spiral machined groove seen in the lower skin holes



Note the rivet tilt and the non-uniform thickness of the bucked tail.

540+08.9~4R+1.0~LSH

Summary of Rivet driven head dimensions measured with a dial caliper.

- The minimum head **diameter** for all 5/32 rivets used in longitudinal body skin lap splices is specified to be: 1.4 x 5/32" = **0.219"** min. per BAC drawing 69-63000.
- Actual measurements:
  - in bay 520-540, 2 of the 15 lower row holes had rivets with tail diameters less than spec.
  - in bay 540-560, 11 of the 15 lower row holes had rivets with tail diameters less than spec.
  - in bay 580-600, 8 the of 15 lower row holes had rivets with tail diameters less than spec.
  - in terms of the holes with cracks, 14 of the 32 cracked holes had rivets with tail diameters less than the specification minimum.

Summary of Rivet driven head dimensions (continued).

- The minimum and maximum **rivet head height or thickness** for all 5/32 rivets used in longitudinal body skin lap splices is specified to be **0.062" min.** and **0.092" max**. per BAC drawing 69-63000.
- Actual measurements:
  - in bay 520-540, 1 of the 15 lower row holes had rivet with tail thickness higher than spec.
  - in bay 540-560, 9 of the 15 lower row holes had rivets with tail thickness higher than spec; and 1 of the 15 had rivet tail thickness less than specification minimum.
  - in bay 580-600, 9 of the15 lower row holes had rivets with tail thickness higher than spec
  - in terms of the holes with cracks, 12 of the 32 cracked holes had rivets with thickness higher than the specification maximum and 1 rivet with thickness lower than the spec. mimimum..

Part 2: Summary of Key Results from Rivet Installation and Hole Quality Studies

The cross sections of the rivets as installed showed that:

- during installation, the rivet could bulge into the space between the lower and outer skins, particularly when the hole diameter in the lower skin was smaller than that in the outer skins or when the lower skin had a groove present as seen in all the holes examined;
- this rivet bulging pushed the lower skin outward and caused local bending of the skin;
- metal debris was present between the faying surfaces of the lower and outer skins;

The above three factors namely, lower skin bending at the hole, grooves in the hole, and metal debris, all serve as sites of local stress concentrations and can act as independent crack initiation sites.

However, the observation of preferntial cracking in the lower two quadrants of the holes, is not yet explained from the studies to-date.

The rivet bucked tail measurements showed that:

- about 40% of the cracked holes had under-driven rivets;

The significance of this result needs to be explored further.

Part 3: Scanning Electron Microscope Fractography of Cracks

Table of Holes/Cracks Examined

LSH Hole Location	Crack #	Max. Crack Length (in)	Max Crack Width (in)	Type of Origins	Defects/Flaw(s)
540+05.7~4R+1.0	1	0.153	0.043	Hole surface, Corner & Faying surface	Light fretting in hole; Gouge/groove at hole corner and surface
	2	0.033	0.020	Faying surface near corner	Not clear
	3	0.034	0.024	Hole corner	Gouge/groove at hole corner
	4	0.139	0.035	Hole corner and multiple faying surface origins	Gouge/groove at corner; light scuff marks on surface
540+06.8~4R+1.0	1	0.188	0.044	Hole corner Hole surface	Gouge/scores
	2	>0.084	0.031	Hole corner Faying surface	Gouge/scores at hole corner; Cause not known since saw cut extended into the crack

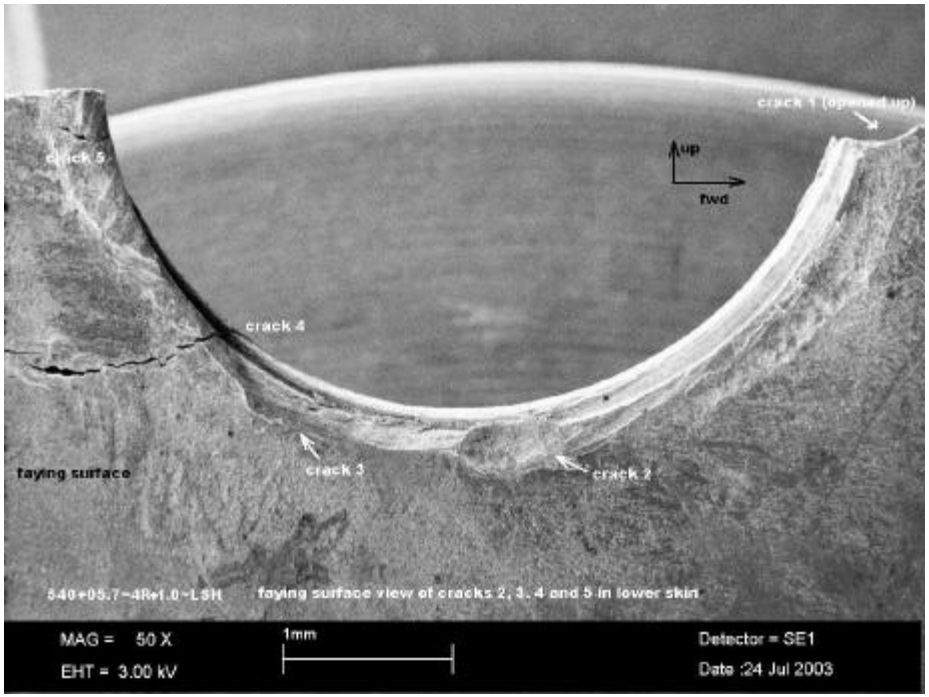
Part 3: Scanning Electron Microscope Fractography of Cracks

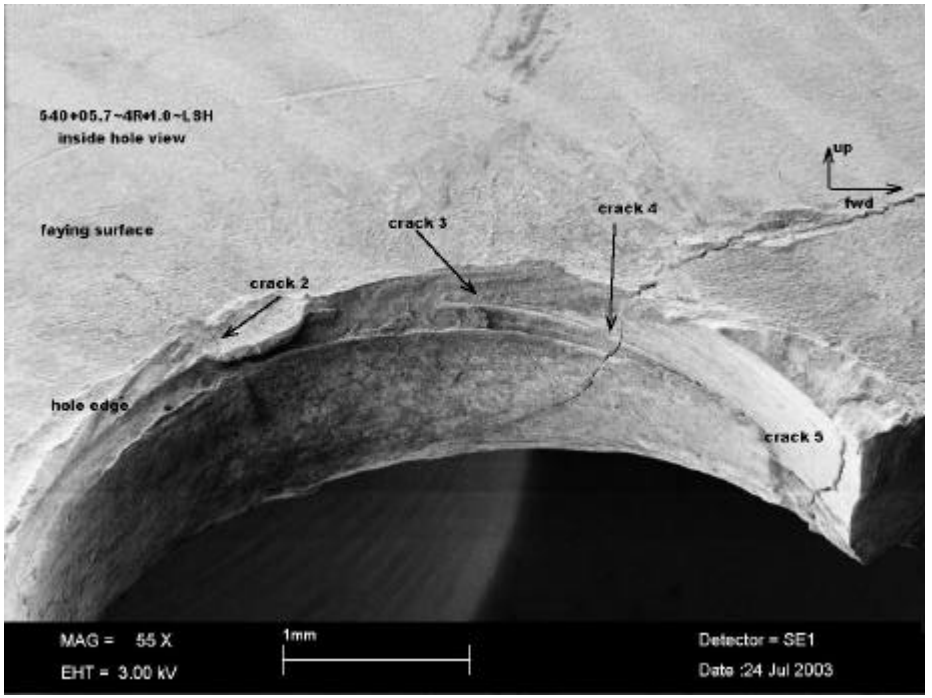
Table of Holes/Cracks Examined

LSH Hole Location	Crack #	Max. Crack Length (in)	Max Crack Width (in)	Type of Origins	Defects/Flaw(s)
540+07.9~4R+1.0	1	0.217	0.044	Hole surface	Light fretting/scuff marks
	2	0.056	0.023	Hole corner (in deformed edge region)	Inside a groove/gouge running along the edge
540+08.9~4R+1.0	1	0.187	0.044	Hole surface and Faying surface (0.014" from corner)	Light fretting in hole surface; Gouge/score along the edge - the origin is just outside this stress raiser
	3	0.070	0.028	Hole corner	Deep scratches/grooved along the edge
540+10.0~4R+1.0	1	0.199	0.044	Hole surface and Faying surface (0.024" from corner)	Scores/scratches in hole; score/fretted area on faying surface

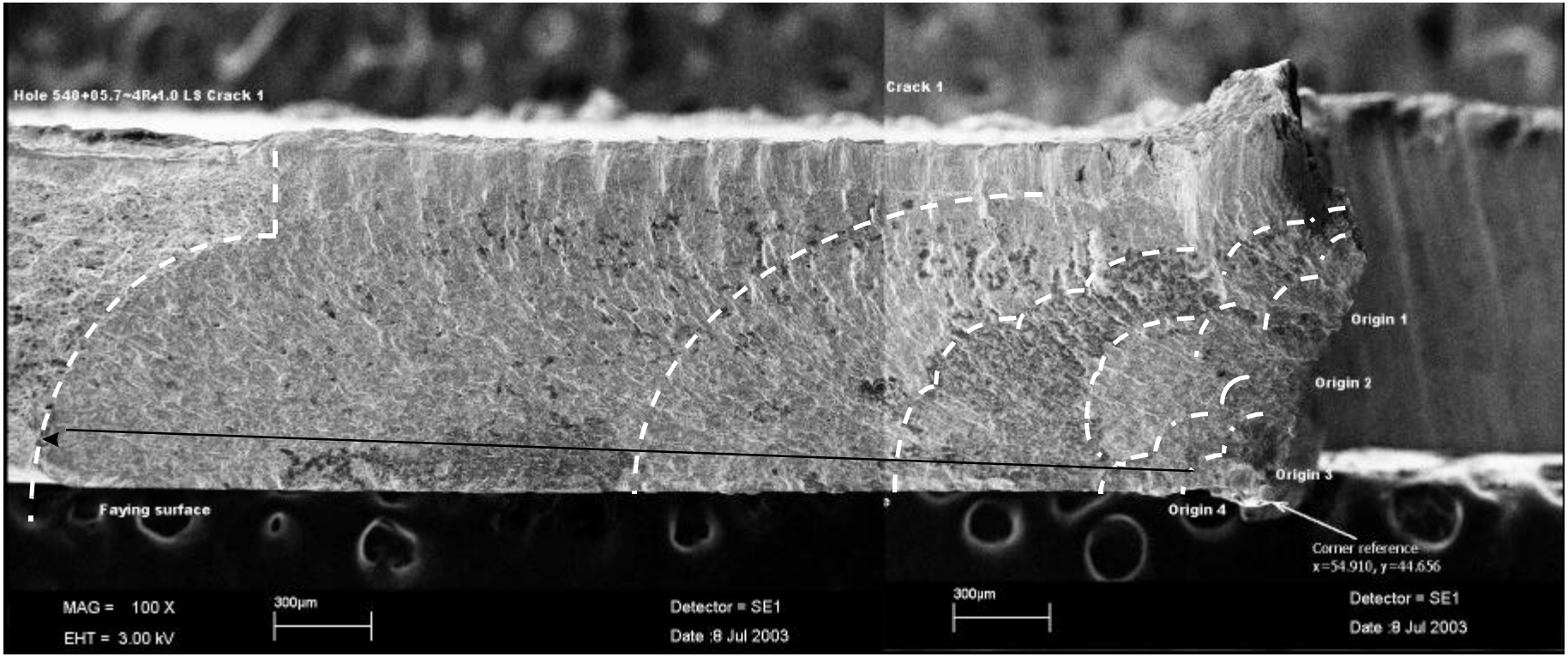
Part 3: Scanning Electron Microscope Fractography of Cracks

Cracks at fastener hole location 540+05.7~4R+1.0~LSH

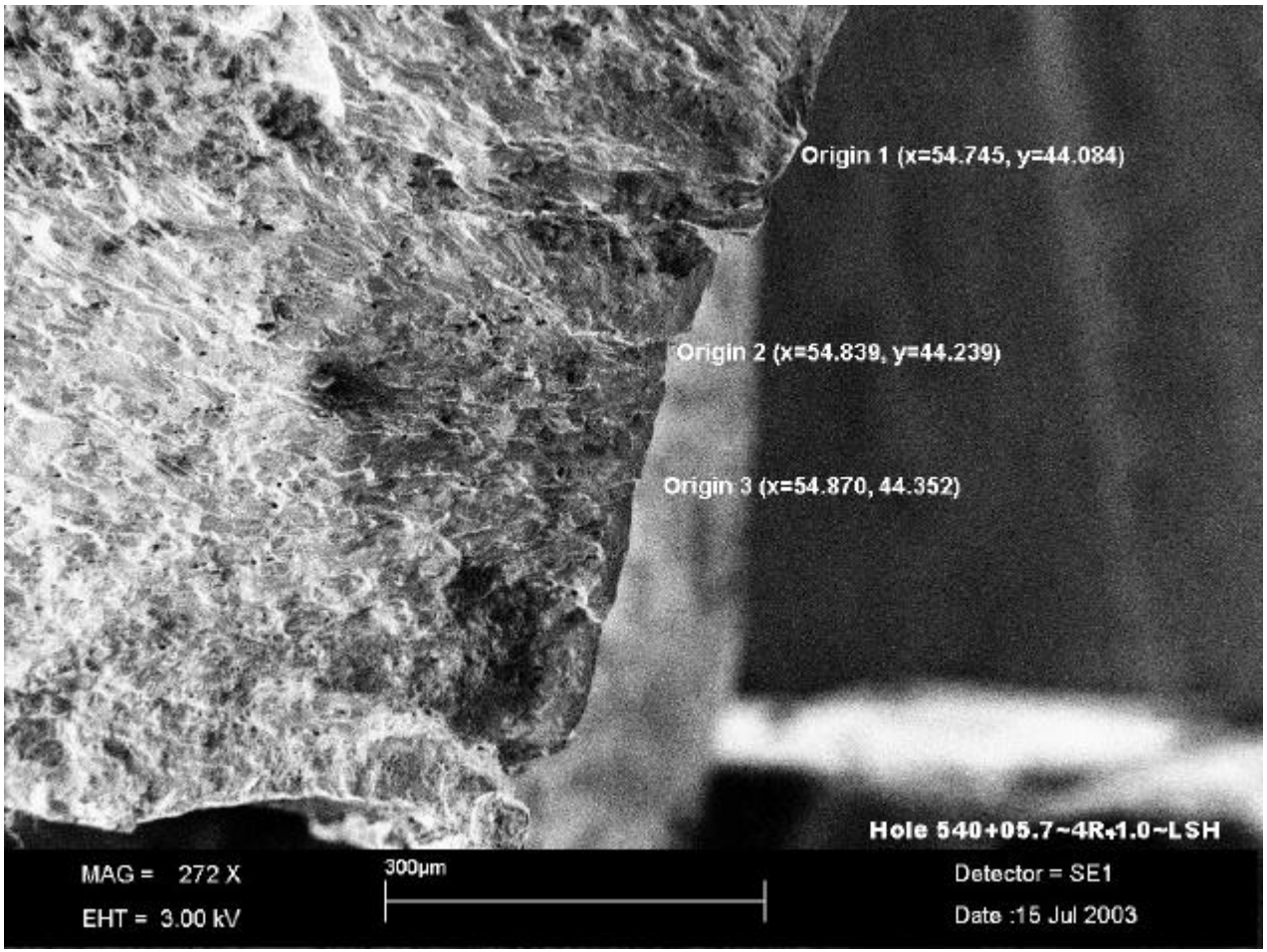




Crack #1 at fastener hole location 540+05.7~4R+1.0~LSH

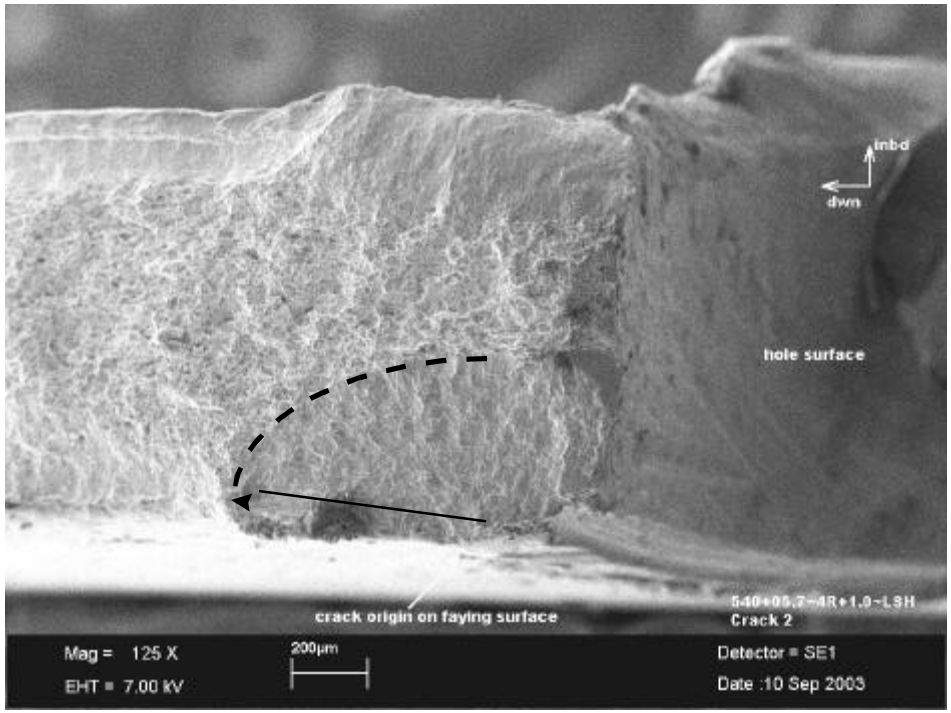


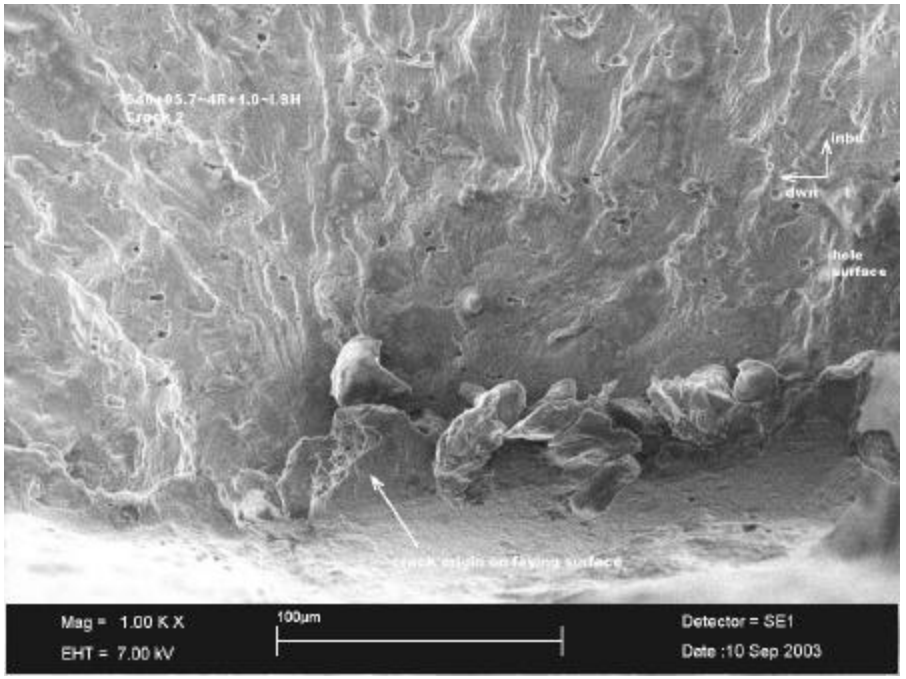
Crack #1 Origins at fastener hole location 540+05.7~4R+1.0~LSH



Part 3: Scanning Electron Microscope Fractography of Cracks

Crack #2 and origin at fastener hole location 540+05.7~4R+1.0~LSH

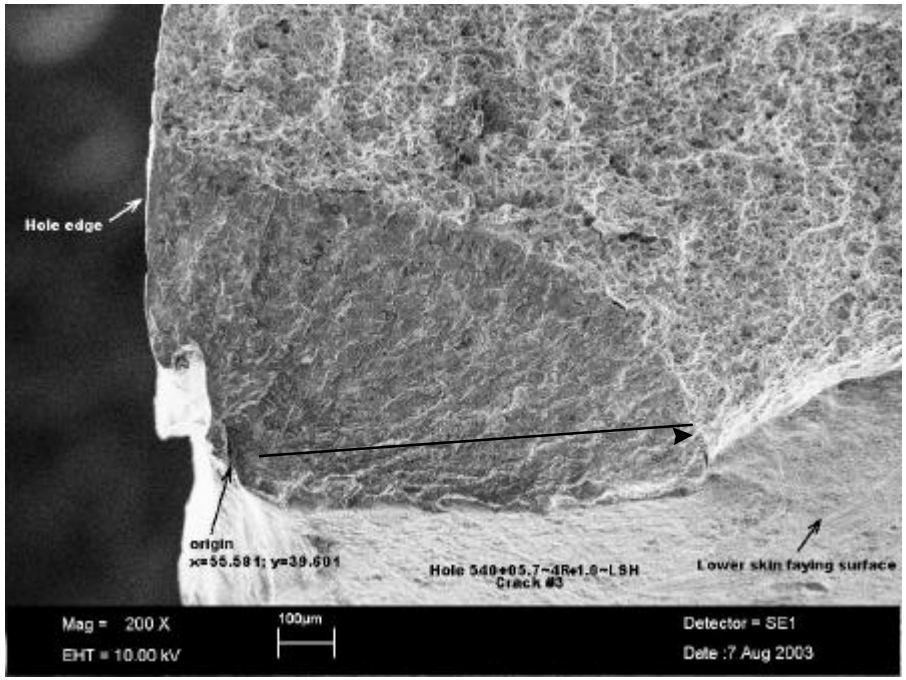


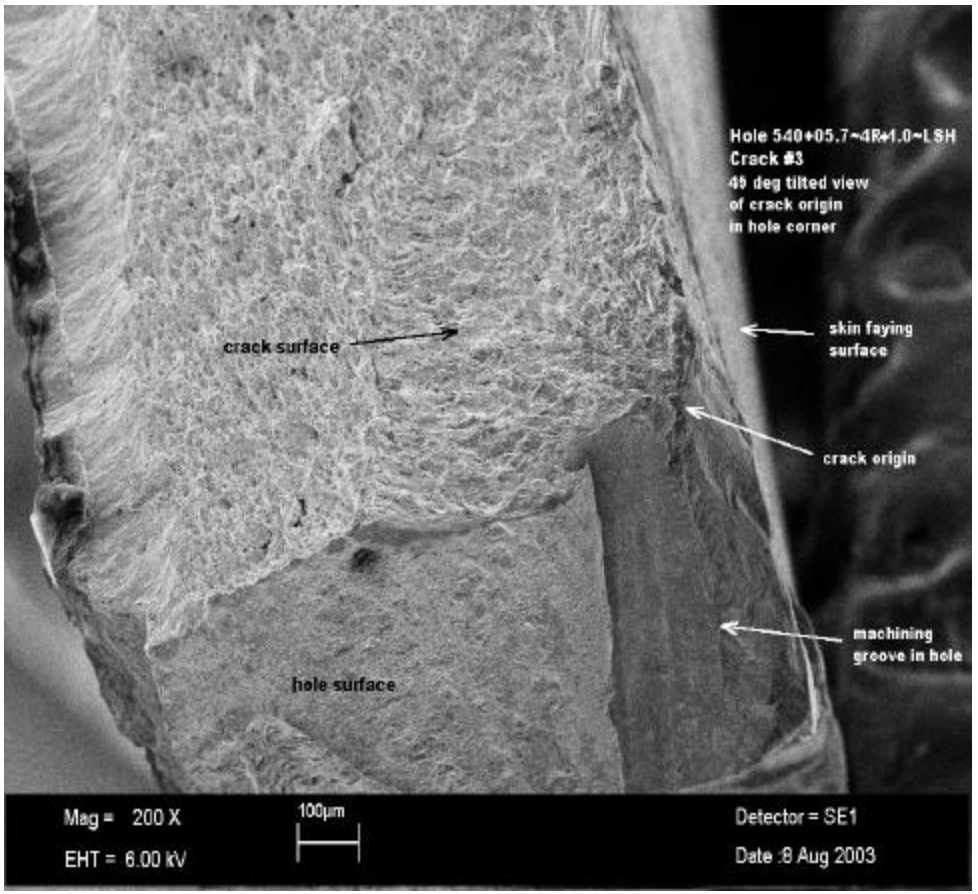


Note the groove present along the hole edge at the skins' faying surface

Part 3: Scanning Electron Microscope Fractography of Cracks

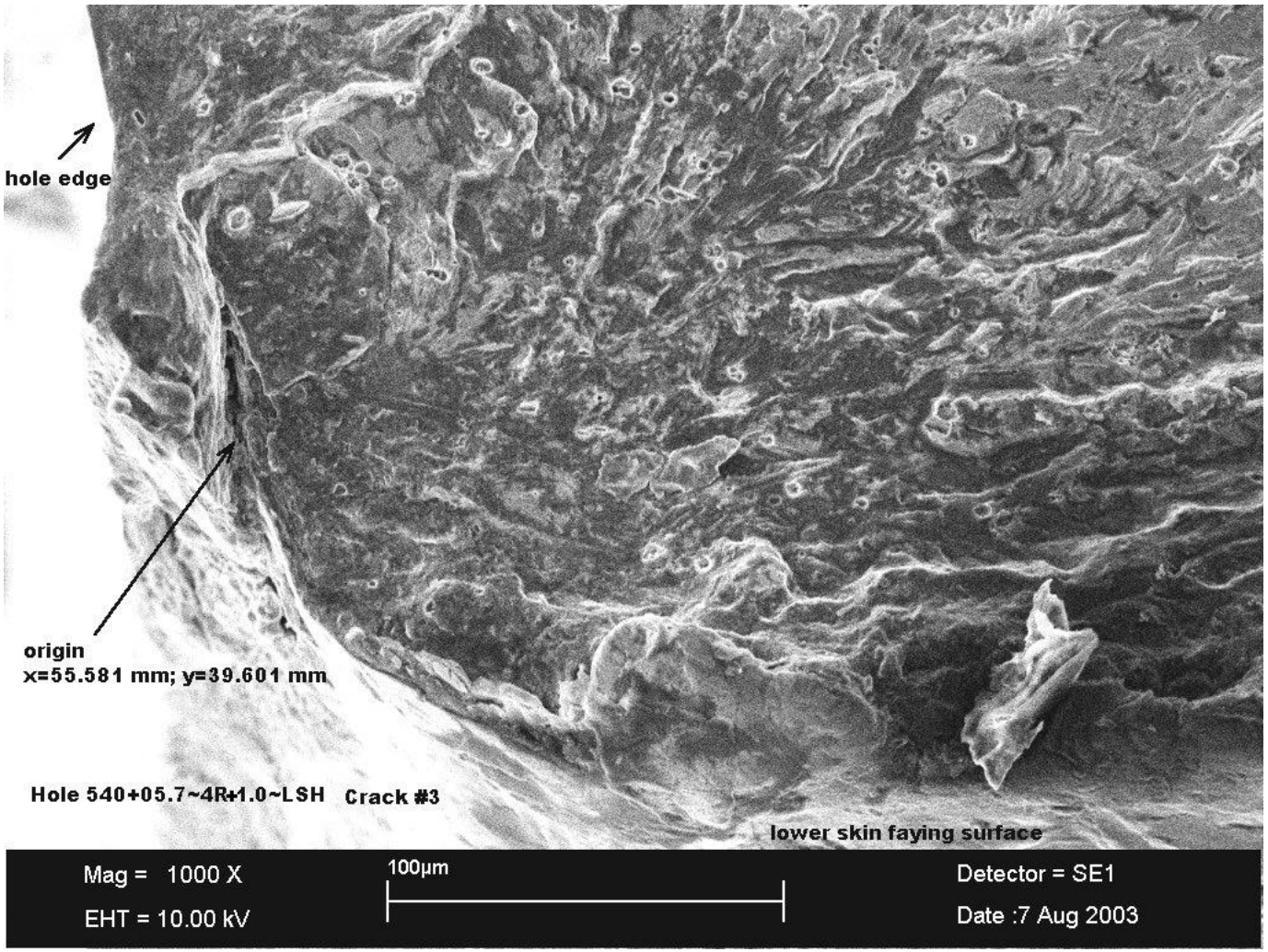
Crack #3 at fastener hole location 540+05.7~4R+1.0~LSH





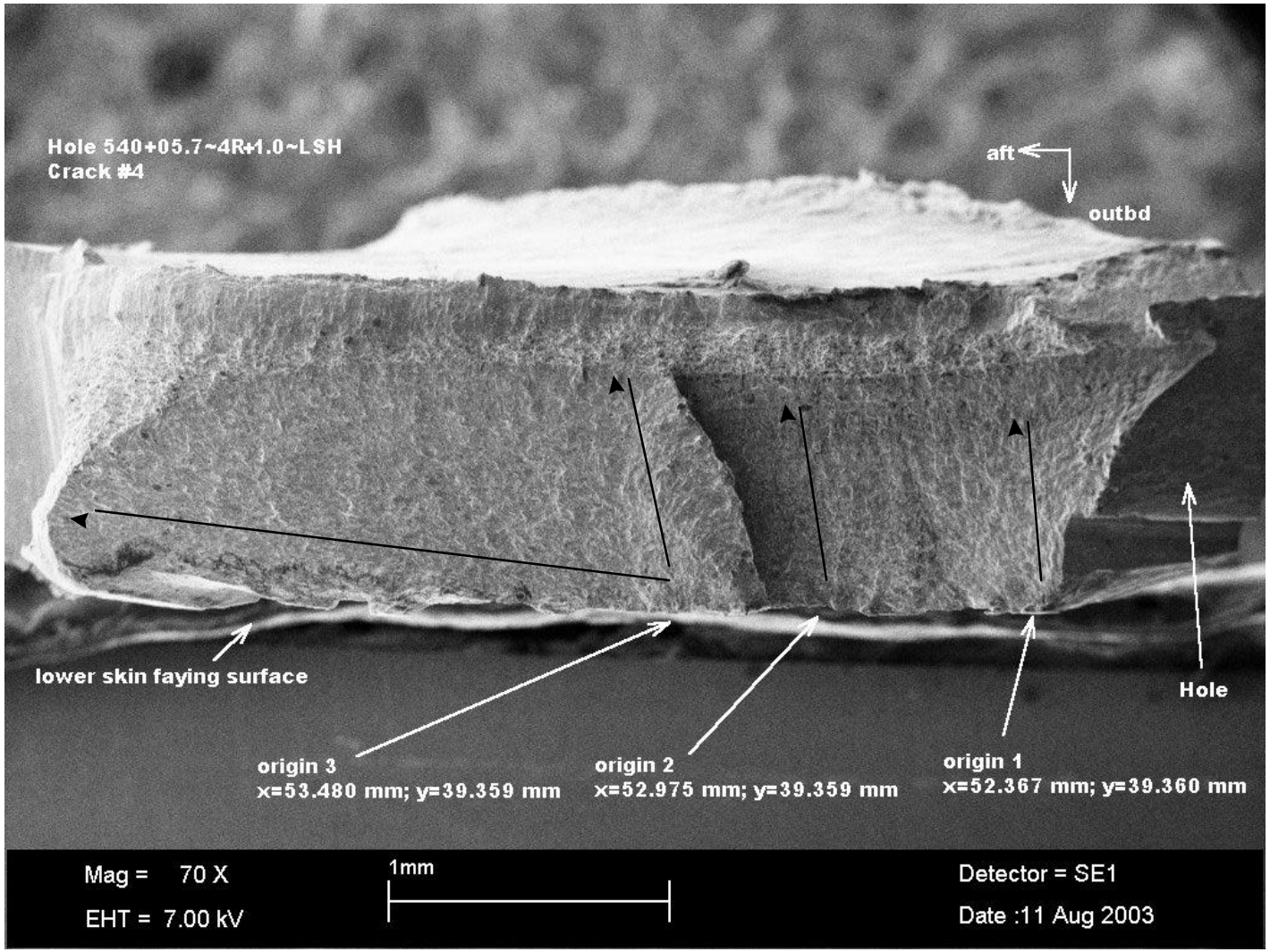
Part 3: Scanning Electron Microscope Fractography of Cracks

- Crack #3 origin at fastener hole location 540+05.7~4R+1.0~LSH



Fastener hole location 540+05.7~4R+1.0~LSH

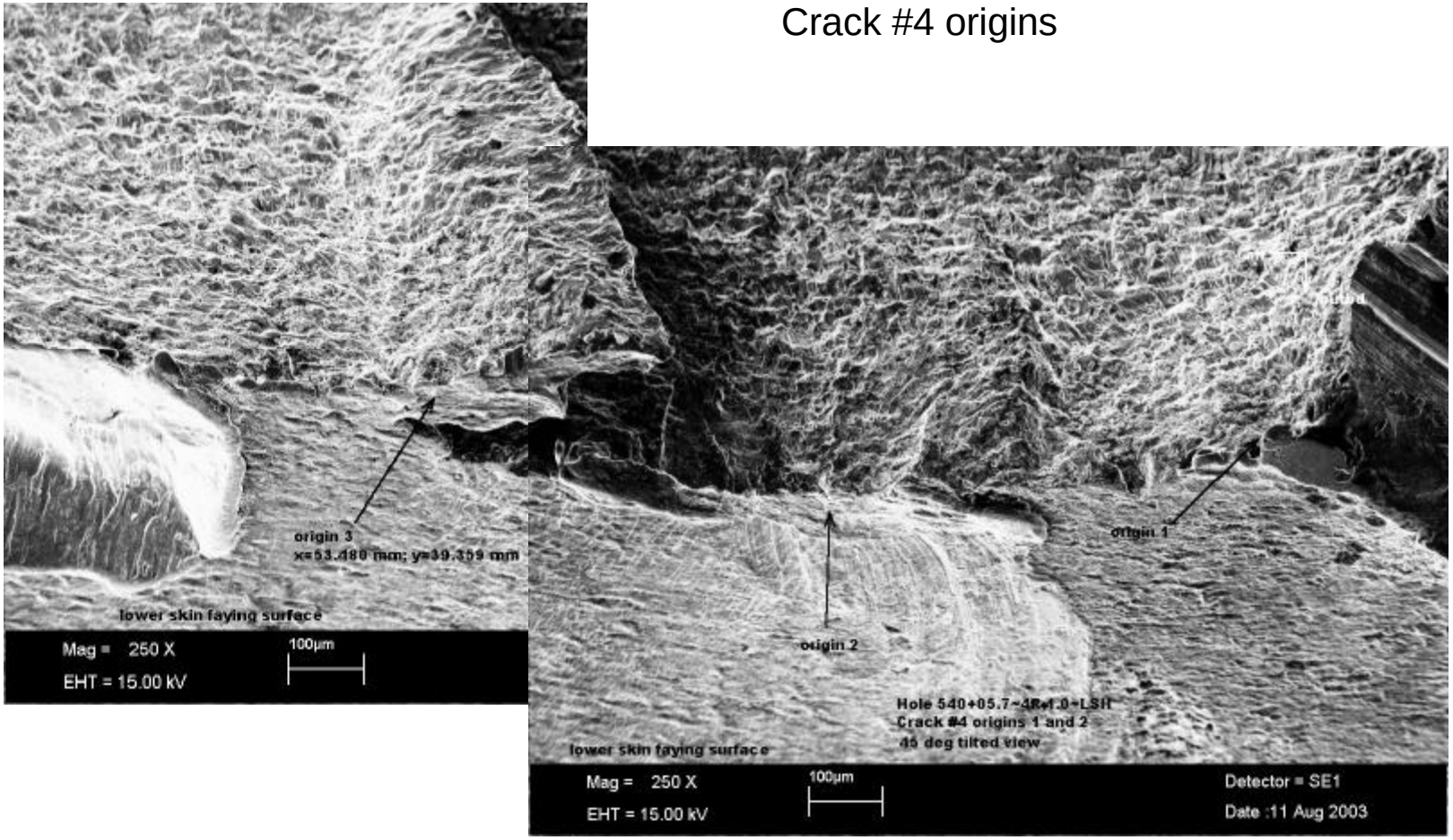
Crack #4



Part 3: Scanning Electron Microscope Fractography of Cracks

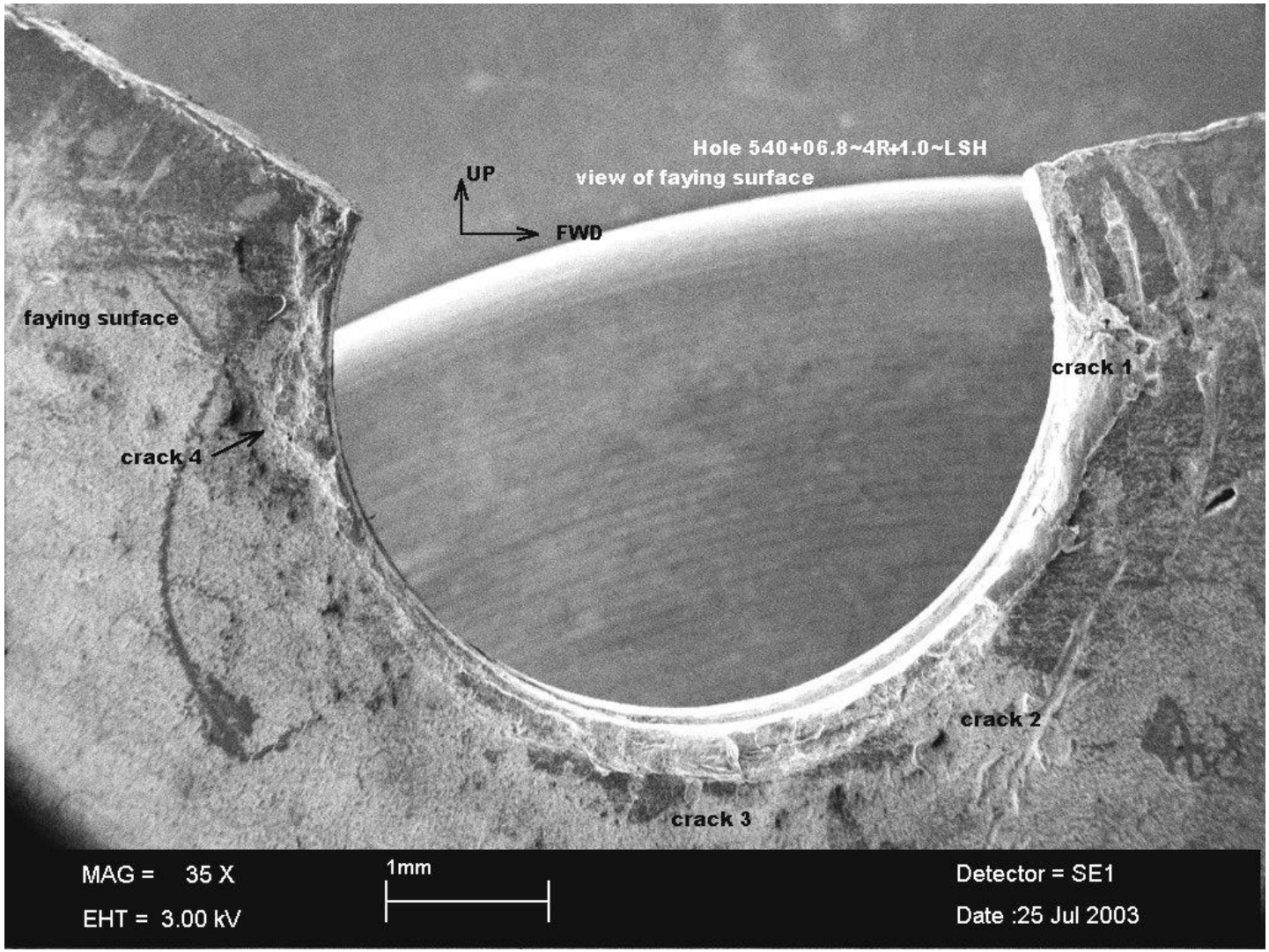
Fastener hole location 540+05.7~4R+1.0~LSH

Crack #4 origins



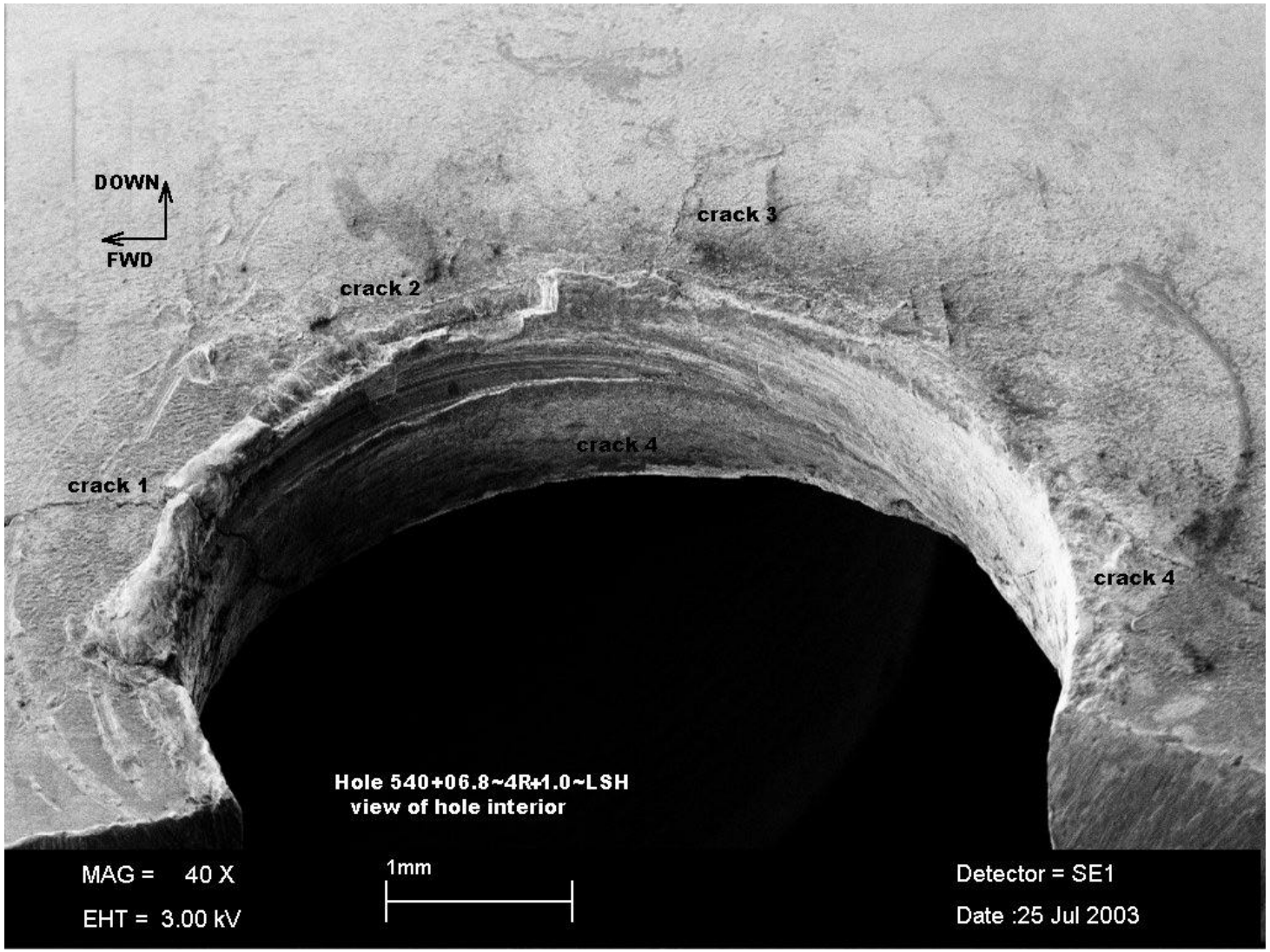
Part 3: Scanning Electron Microscope Fractography of Cracks

Cracks in Fastener hole location 540+06.8~4R+1.0~LSH



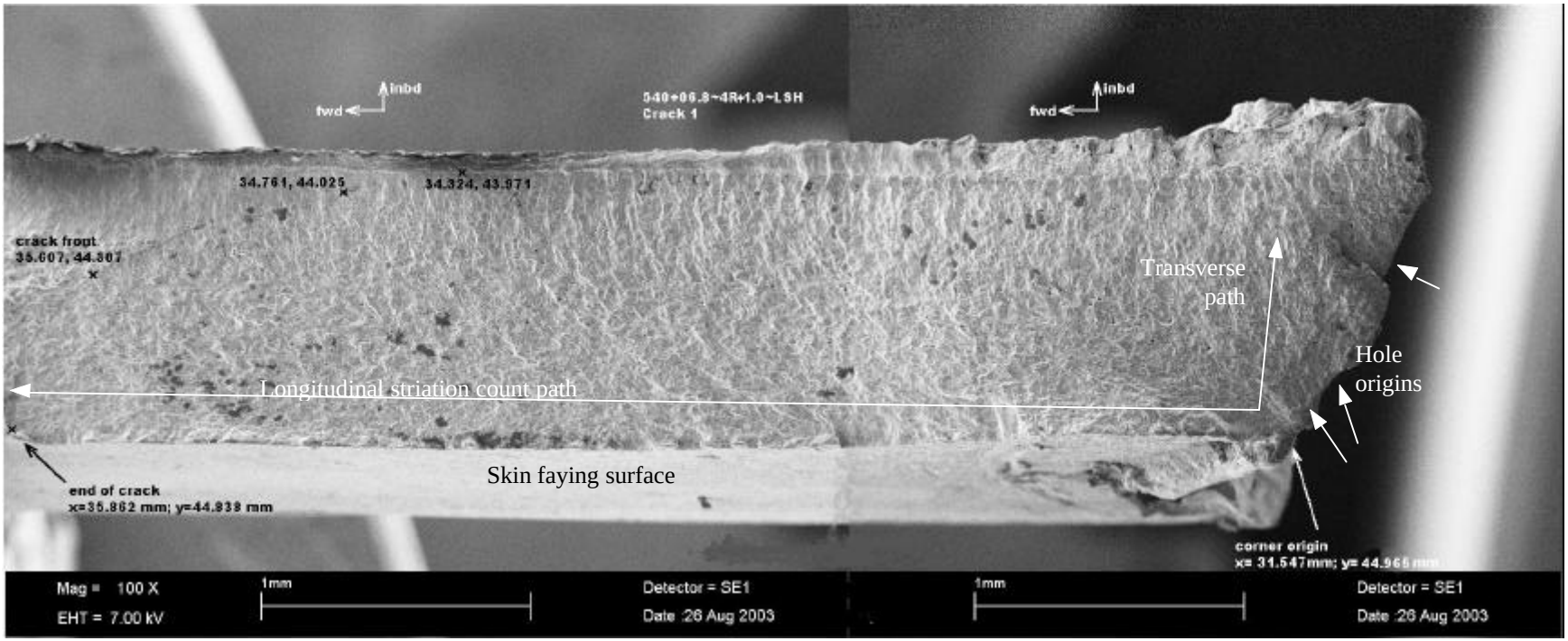
Part 3: Scanning Electron Microscope Fractography of Cracks

Cracks in Fastener hole location 540+06.8~4R+1.0~LSH



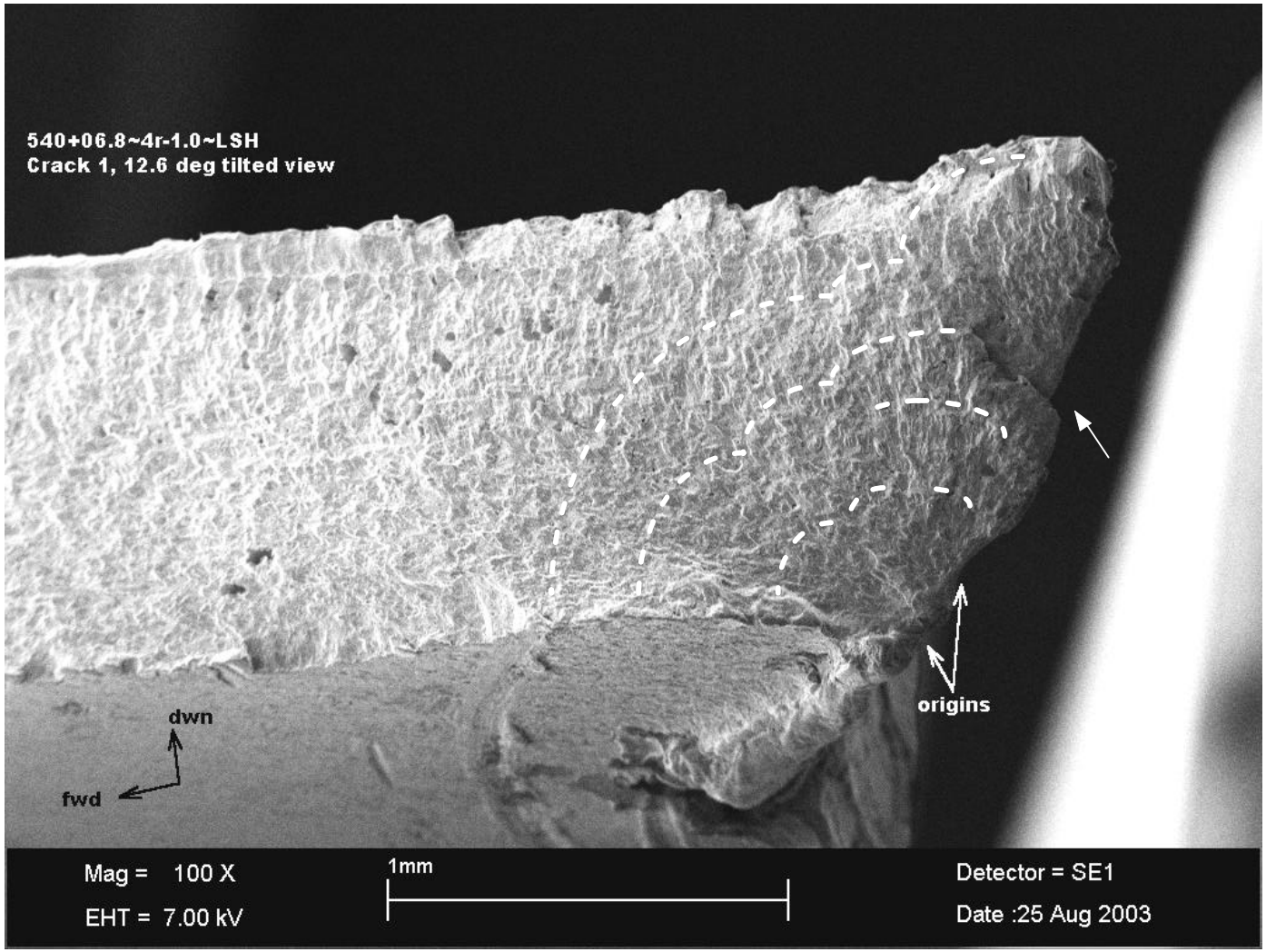
Fastener hole location 540+06.8~4R+1.0~LSH

Crack #1



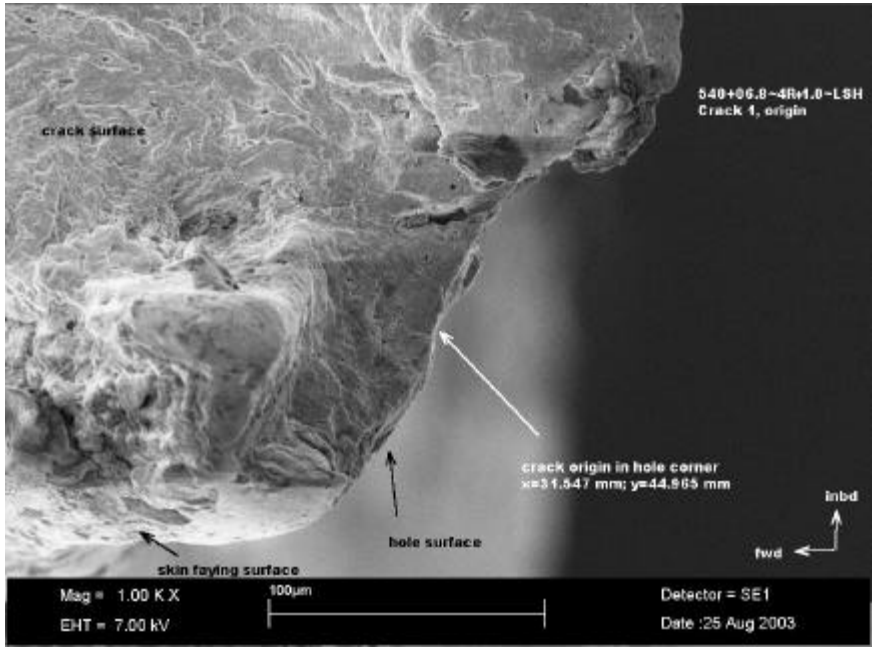
Part 3: Scanning Electron Microscope Fractography of Cracks

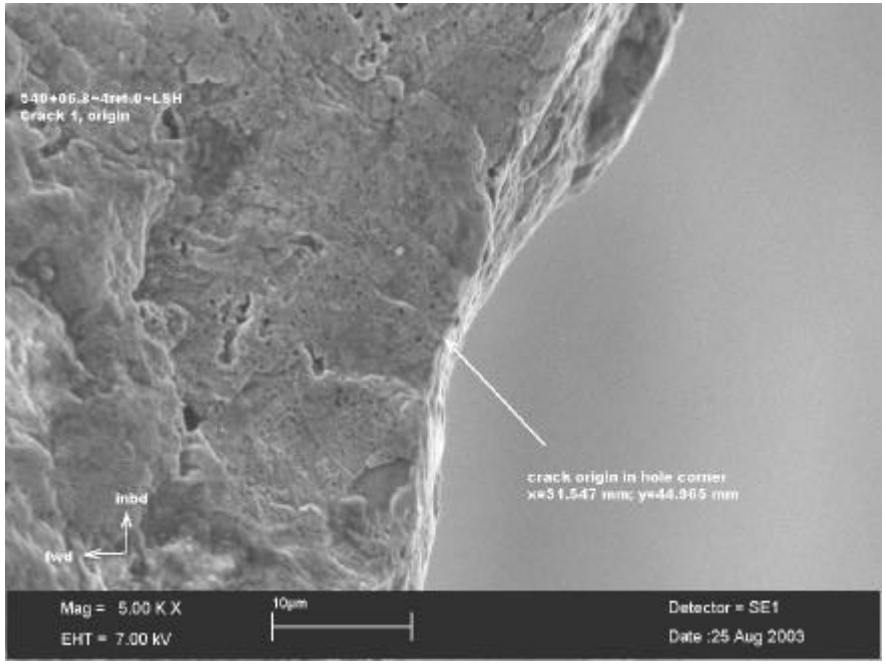
Fastener hole location 540+06.8~4R+1.0~LSH Crack #1



Tilted view of Crack 1, showing the approximate progression of the crack fronts from the multiple origins, during the early stages of crack growth. The main origin appears to be adjacent to the deformed region at the hole corner

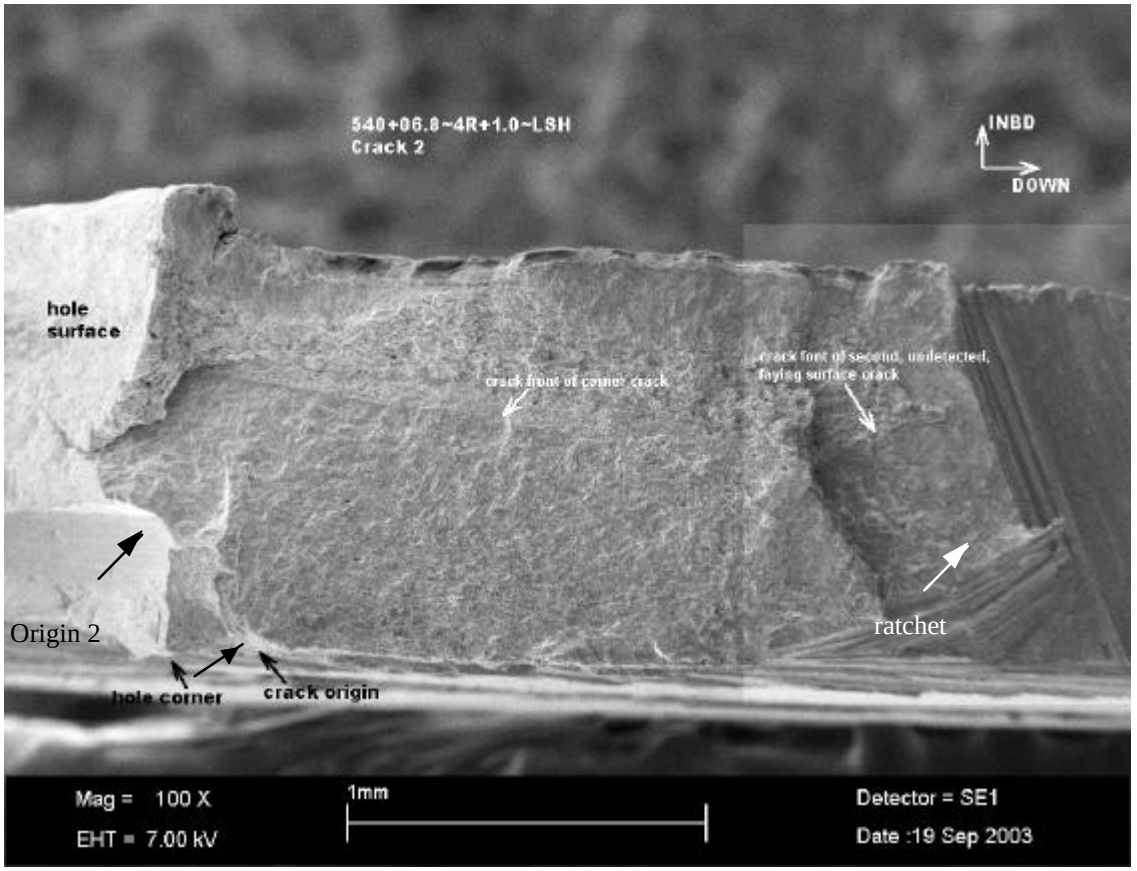
Fastener hole location 540+06.8~4R+1.0~LSH Crack #1 - Origins





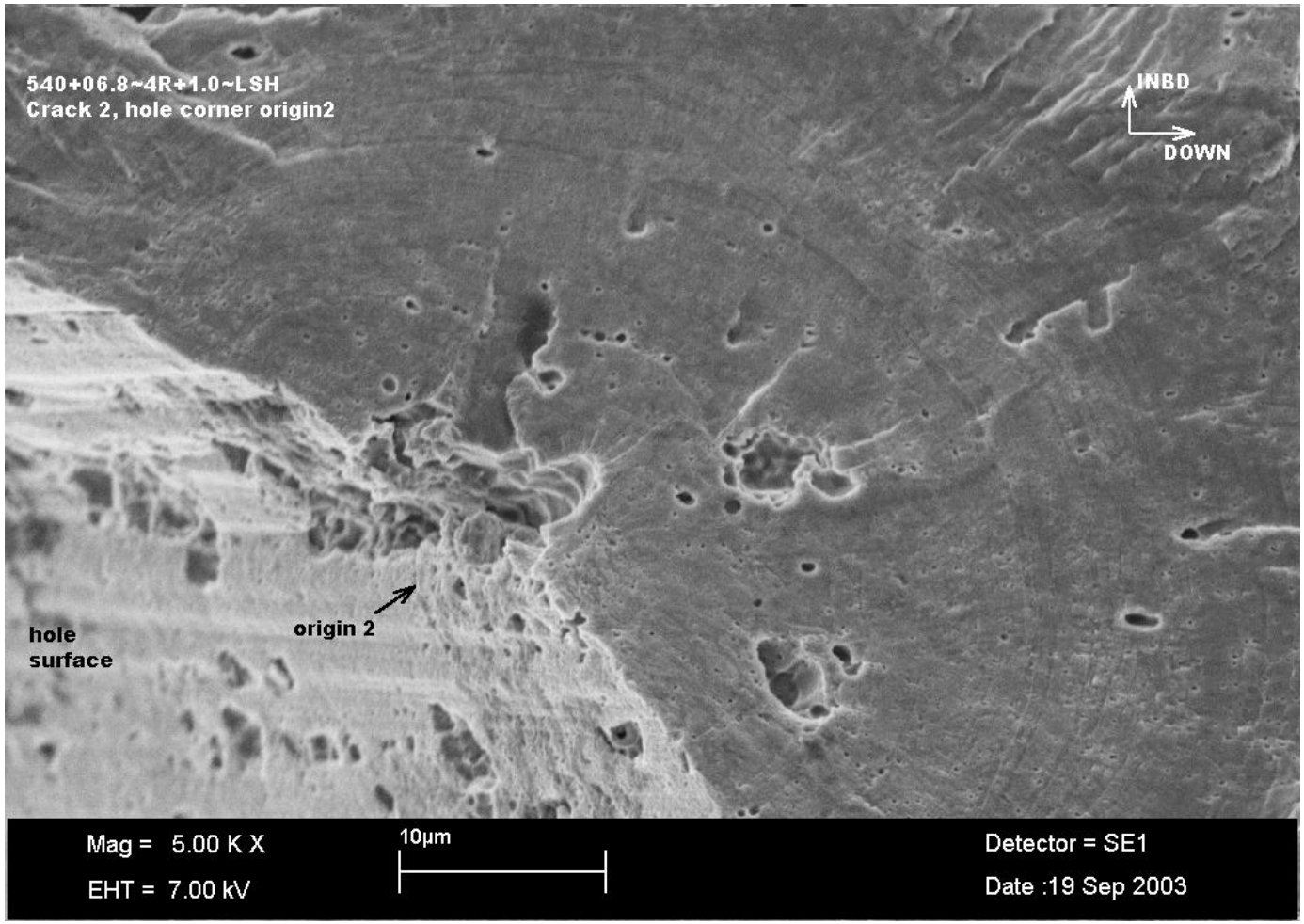
Magnified views of the origins of crack 1 located at the hole corner

Fastener hole location 540+06.8~4R+1.0~LSH Crack #2

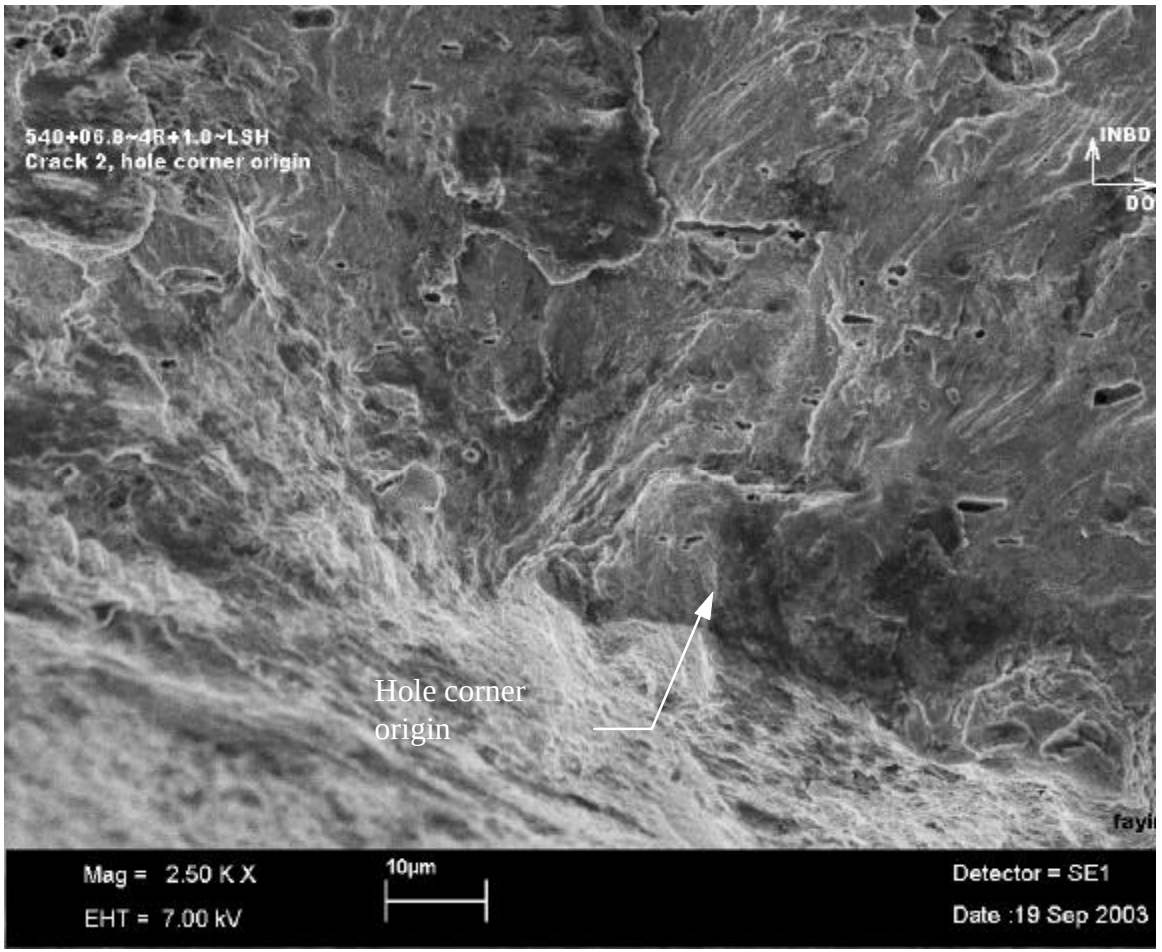


This micrograph shows the presence of two apparently independent cracks, one out of the hole and the other further out on the faying surface, that linked up at the ratchet mark (shear step) identified above. The crack out of the hole had a major origin at the hole corner and a second origin in the inside corner of a machining groove. The origin of the second crack on the faying surface was lost as this crack was not detected under stereomicroscope prior to introducing the saw cut to break open the crack. Striation count measurements have not yet been performed on this crack.

Fastener hole location 540+06.8~4R+1.0~LSH Crack #2 - Origin

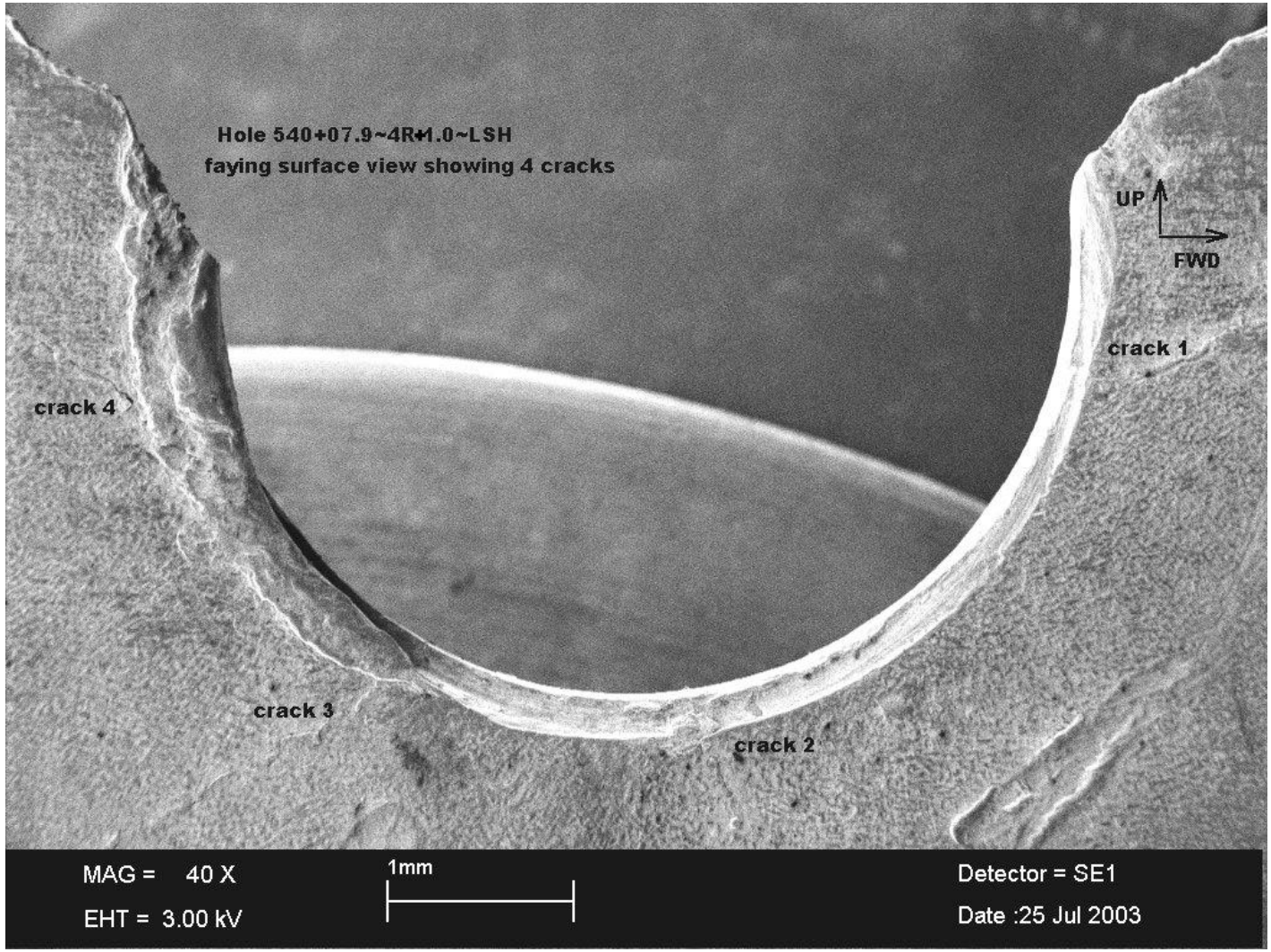


Fastener hole location 540+06.8~4R+1.0~LSH Crack #2 - Origin



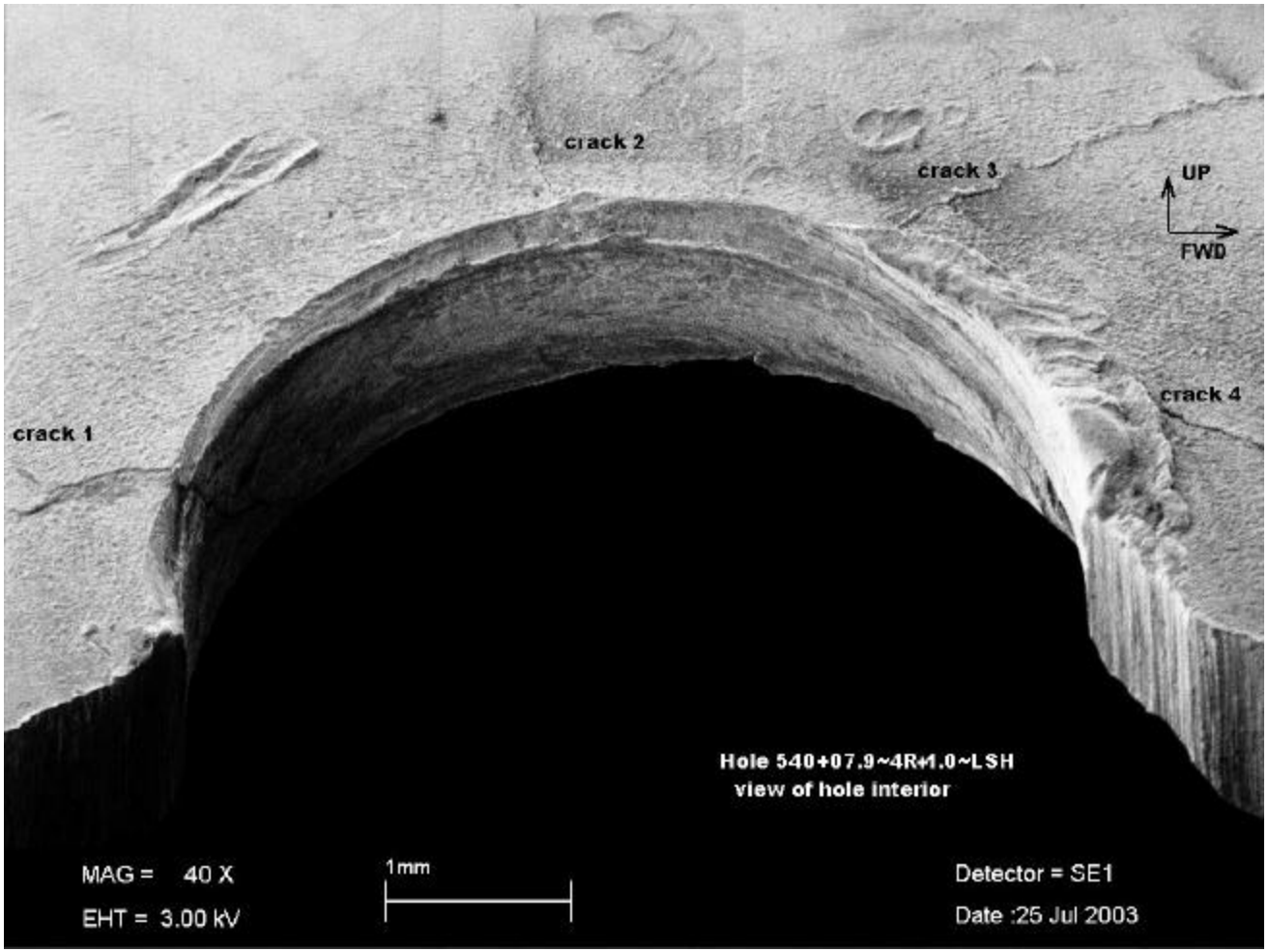
Part 3c: Scanning Electron Microscope Fractography of Cracks

Cracks in fastener hole location 540+07.9~4R+1.0

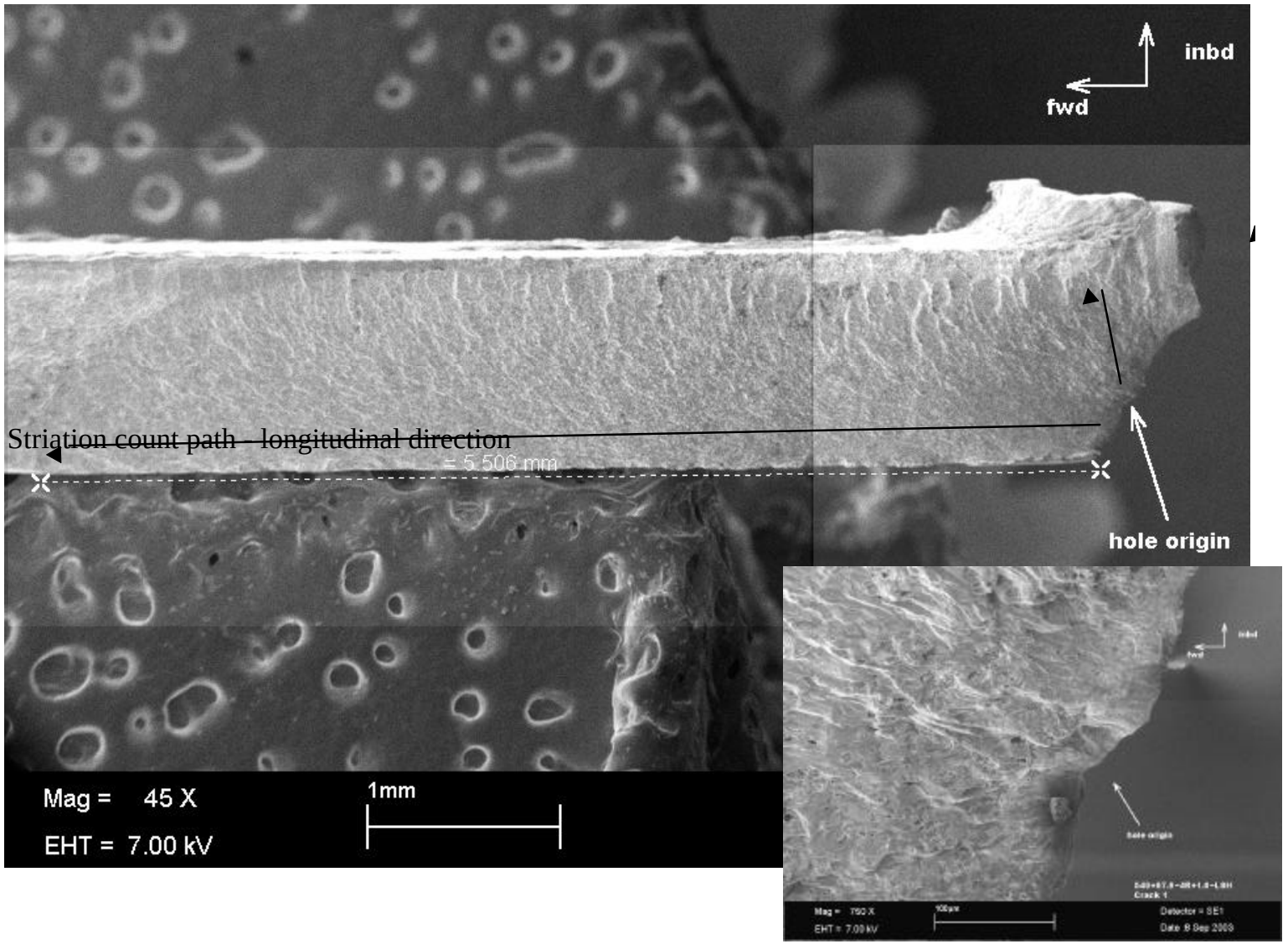


Part 3c: Scanning Electron Microscope Fractography of Cracks

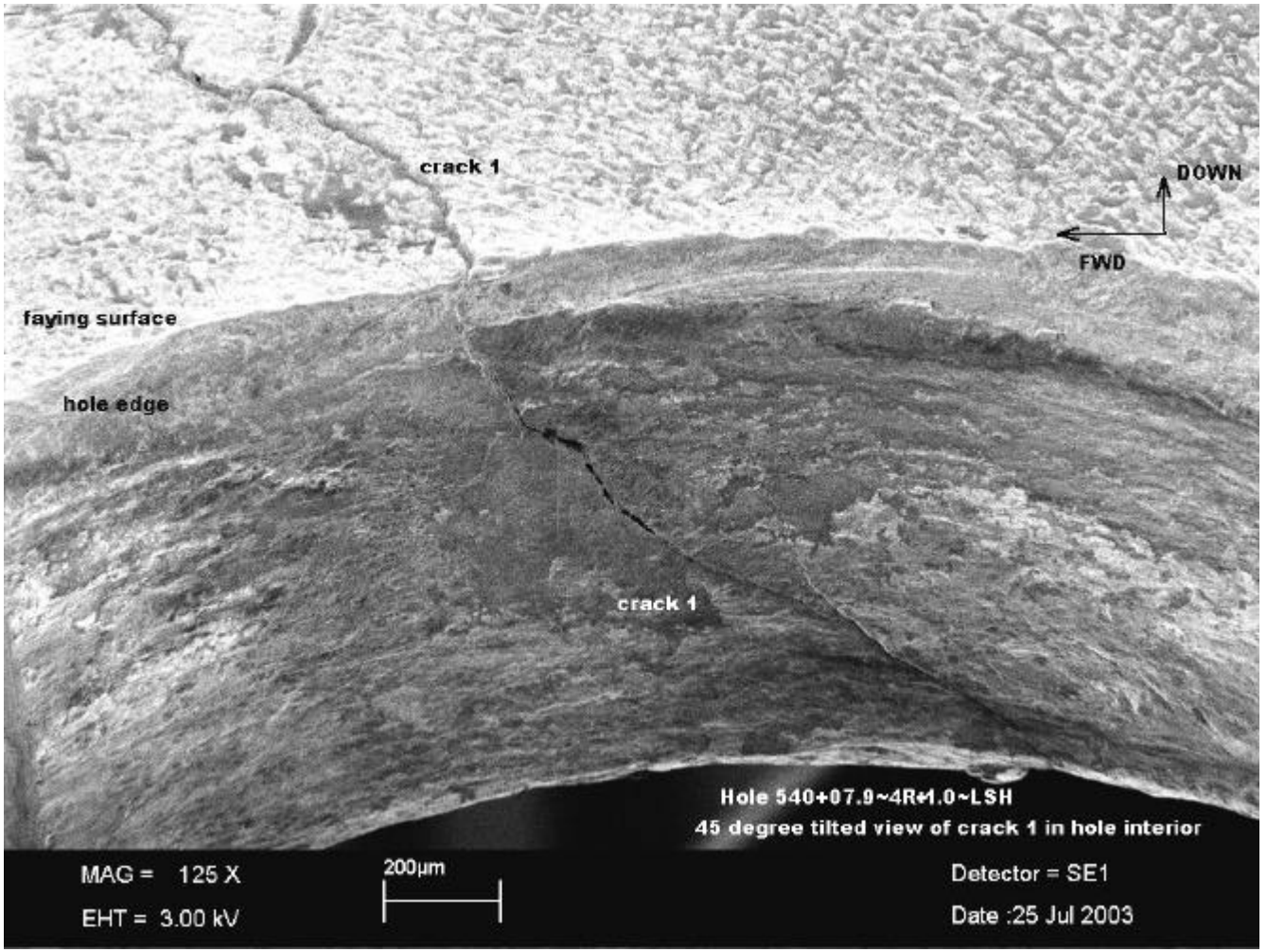
Cracks in fastener hole location 540+07.9~4R+1.0



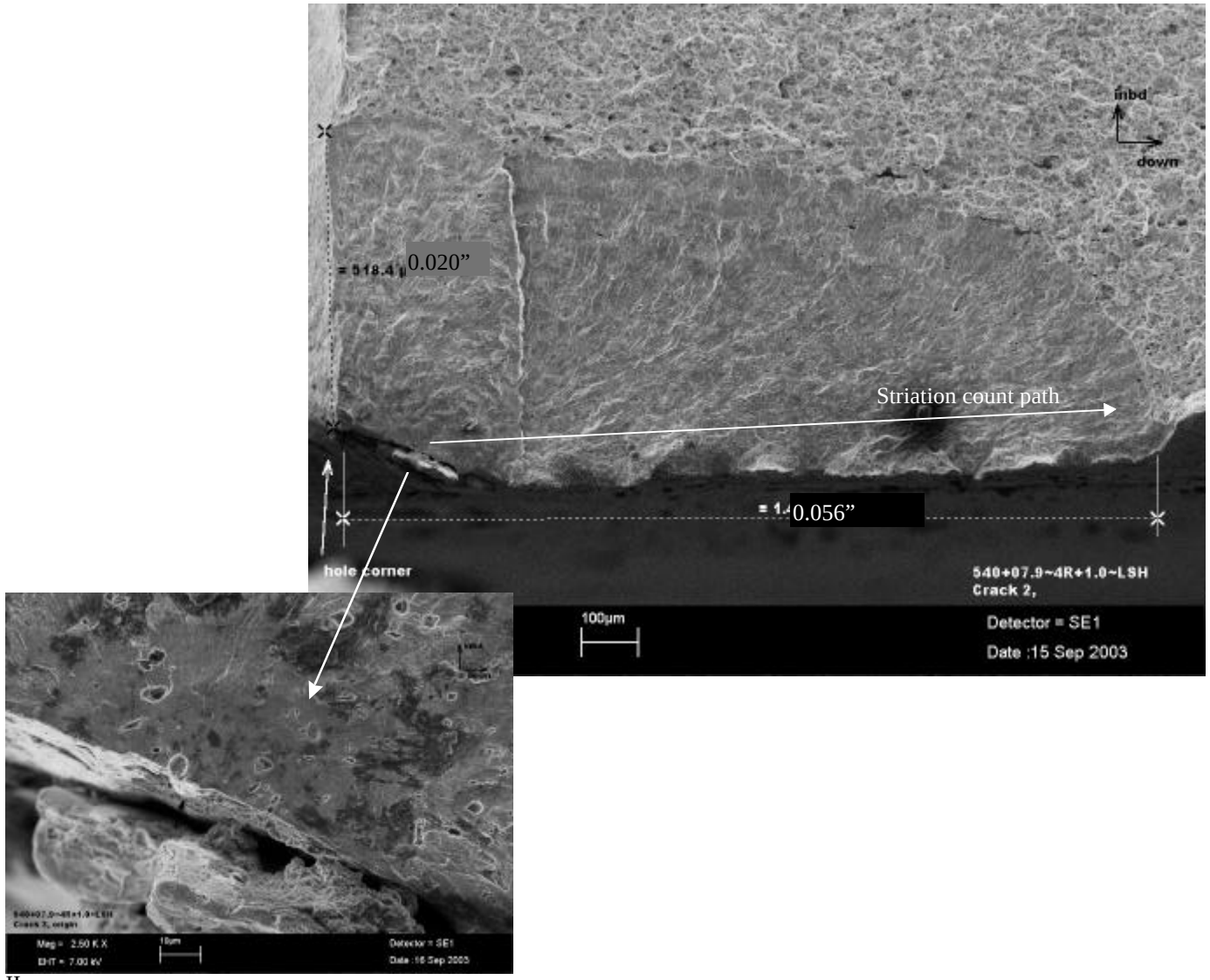
Fastener hole location 540+07.9~4R+1.0 - Crack #1



Fastener hole location 540+07.9~4R+1.0 - Crack #1 in hole interior

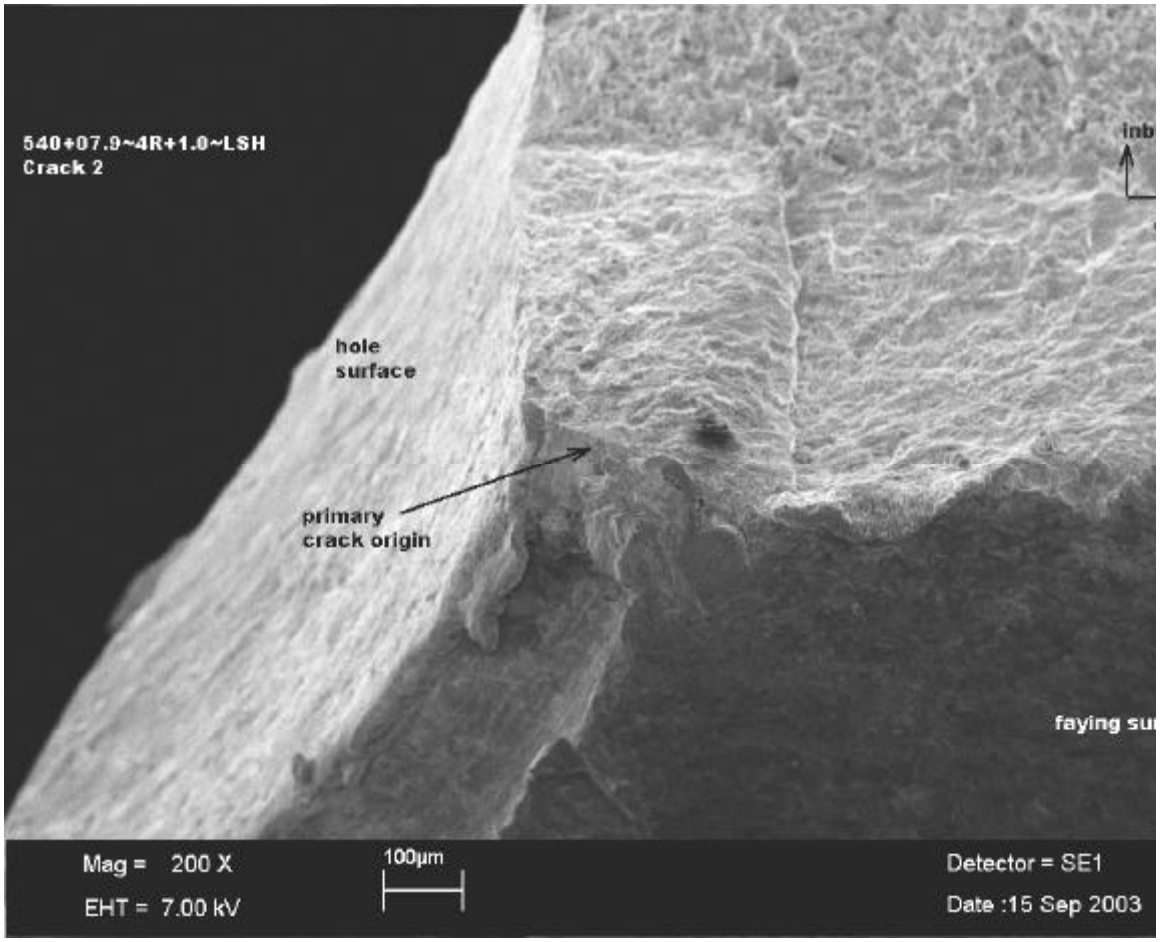


Fastener hole location 540+07.9~4R+1.0 - Crack #2



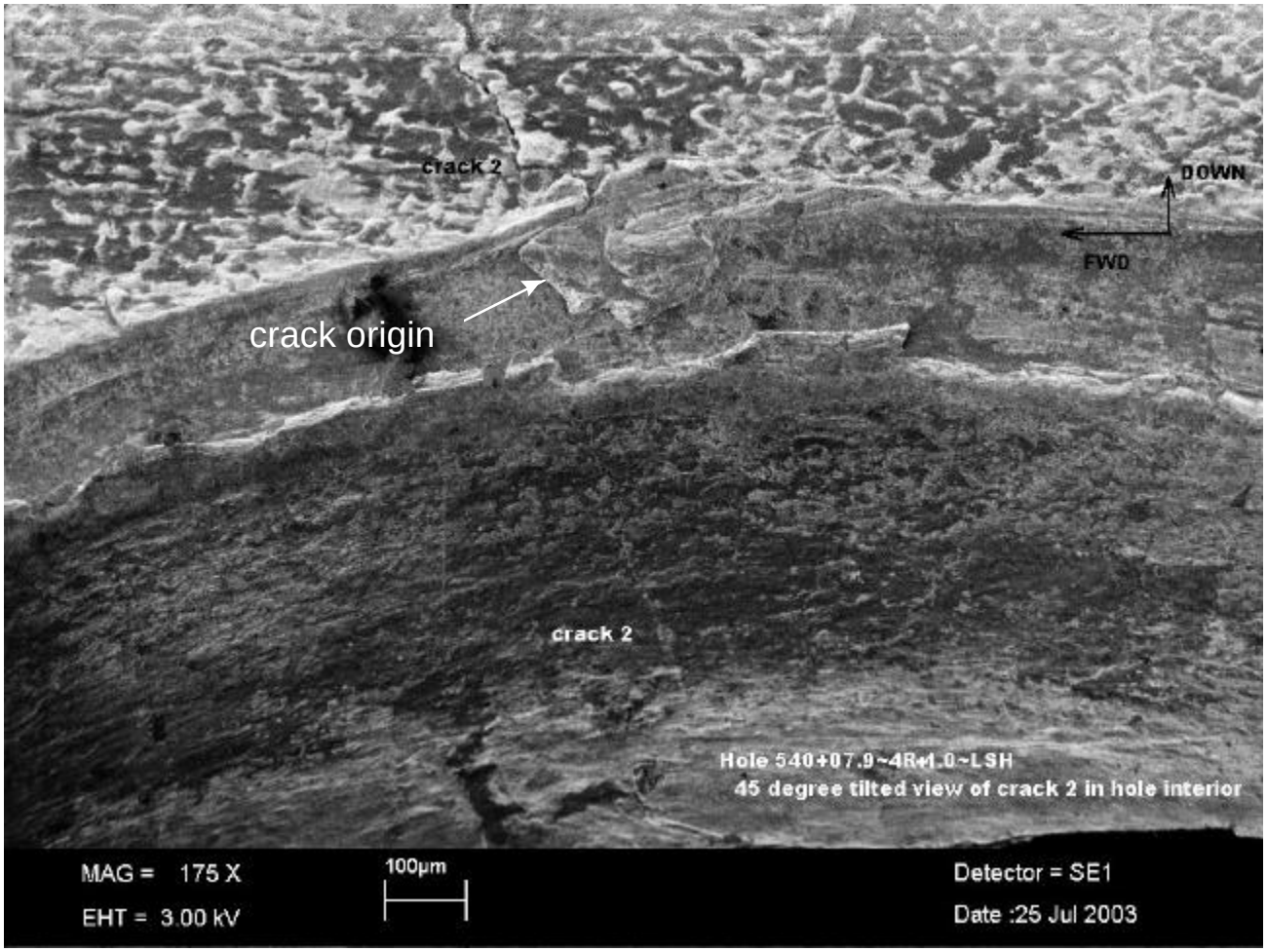
hole corner origin

Fastener hole location 540+07.9~4R+1.0 - Crack #2 Origin - another view of the hole corner



Fastener hole location 540+07.9~4R+1.0 - Crack #2 -

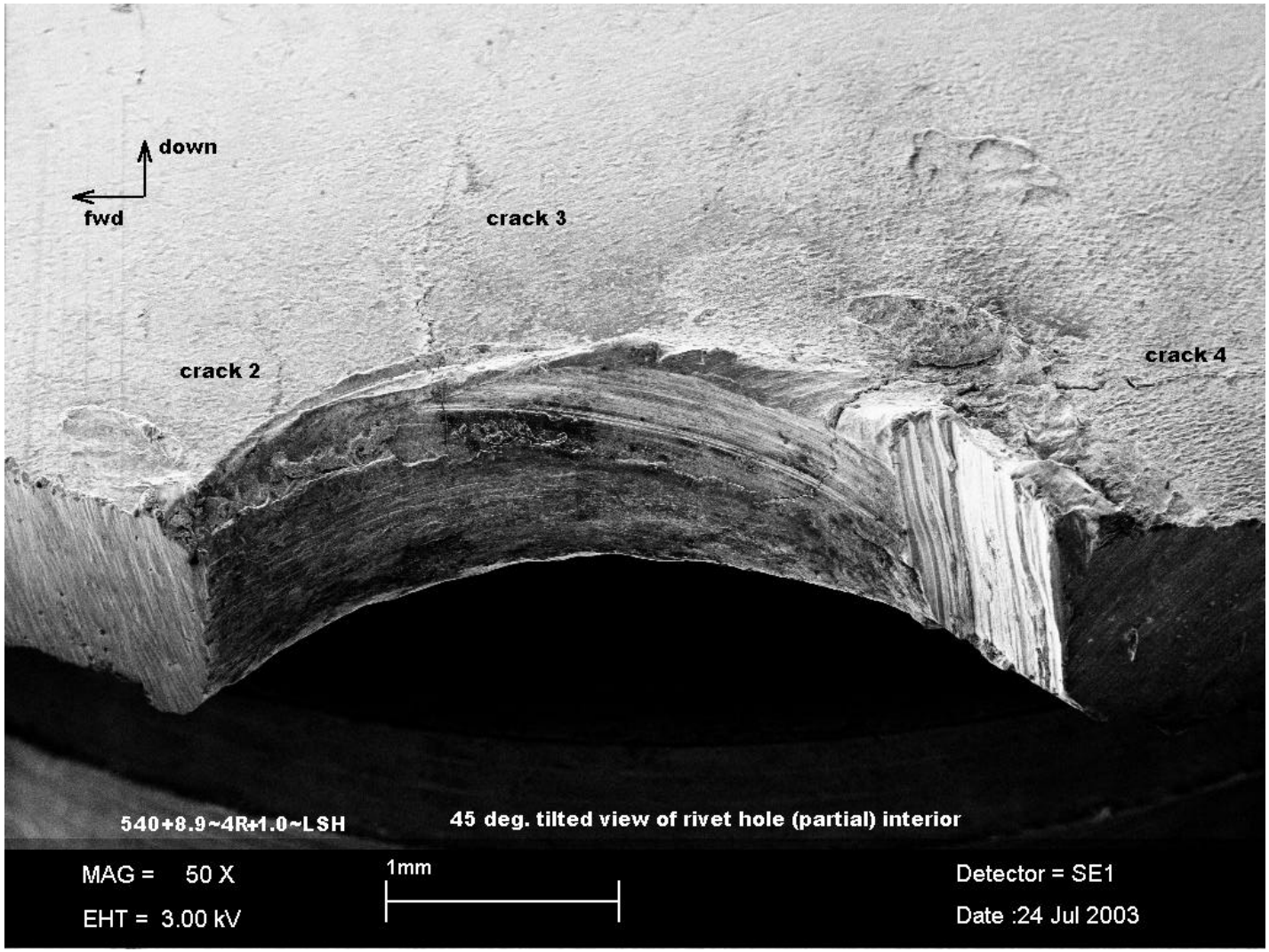
view of the crack in the hole interior



Part 3d: Scanning Electron Microscope Fractography of Cracks

Cracks at fastener hole location 540+08.9~4R+1.0~LSH

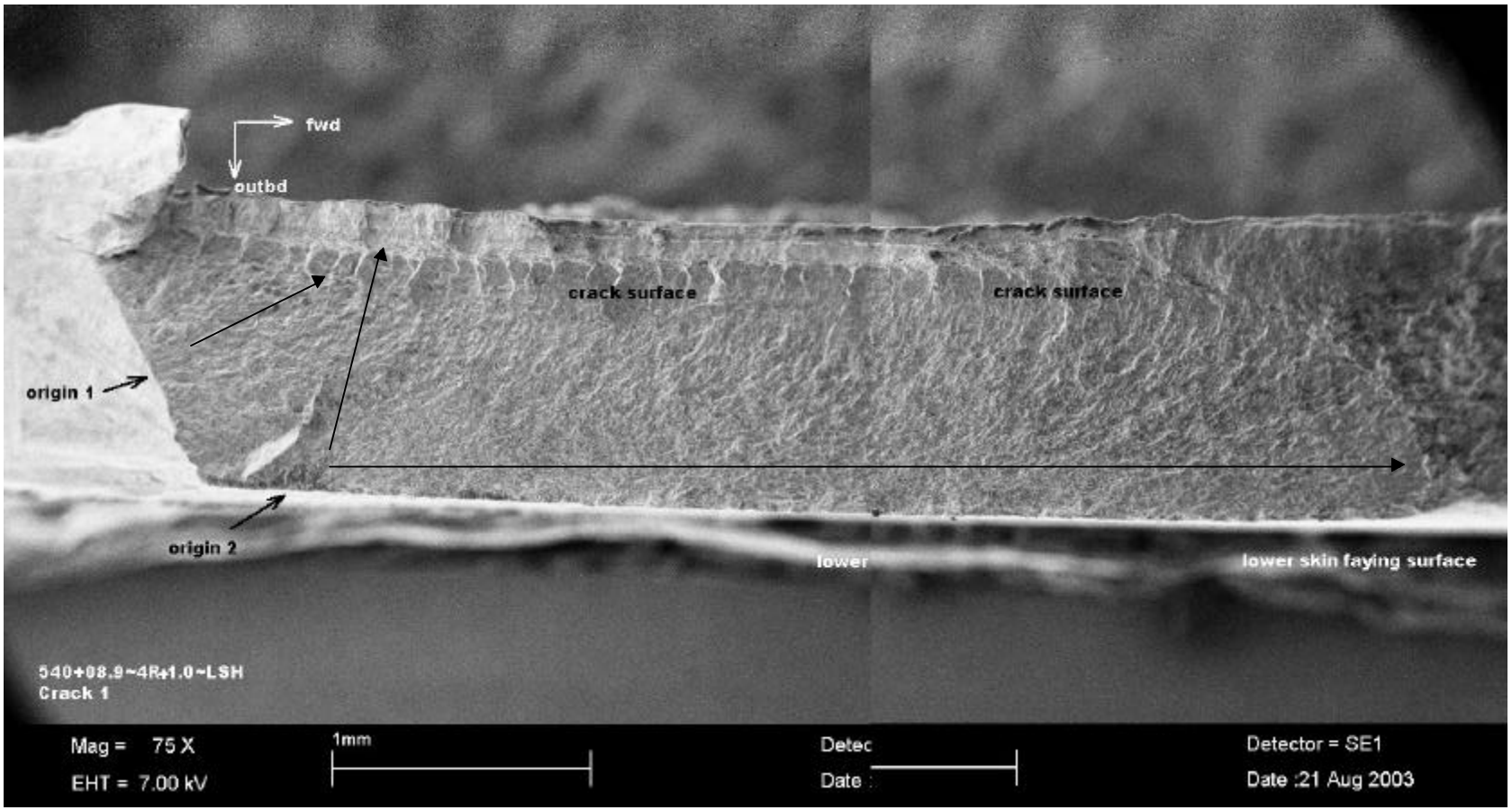
Note that crack 1 had already been excised out of the hole and is not shown

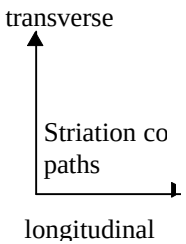


Part 3d: Scanning Electron Microscope Fractography of Cracks

Fastener hole location 540+08.9~4R+1.0~LSH

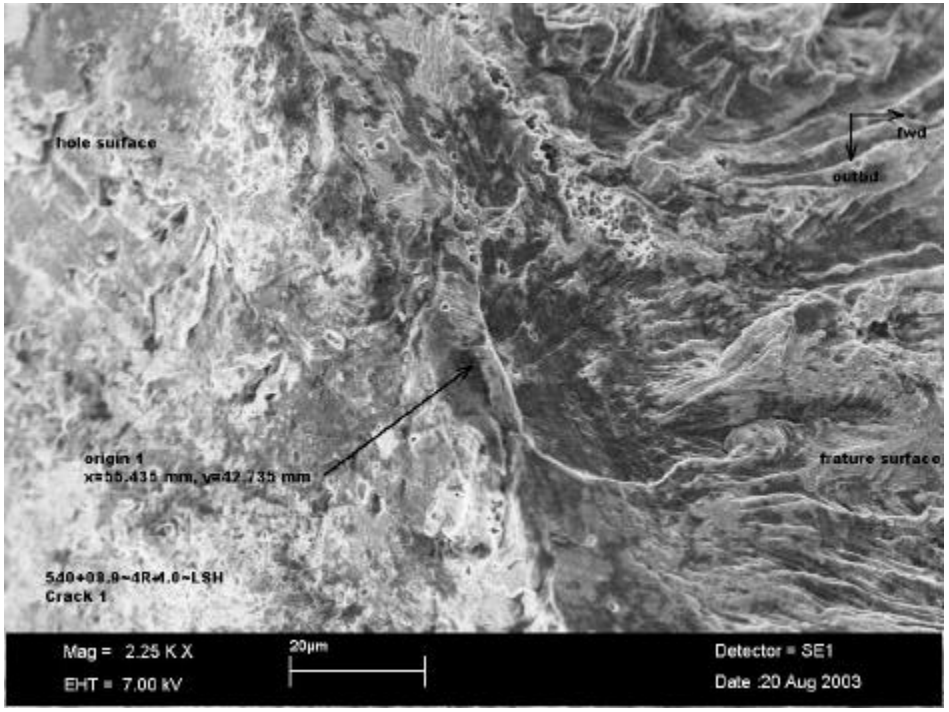
Crack #1

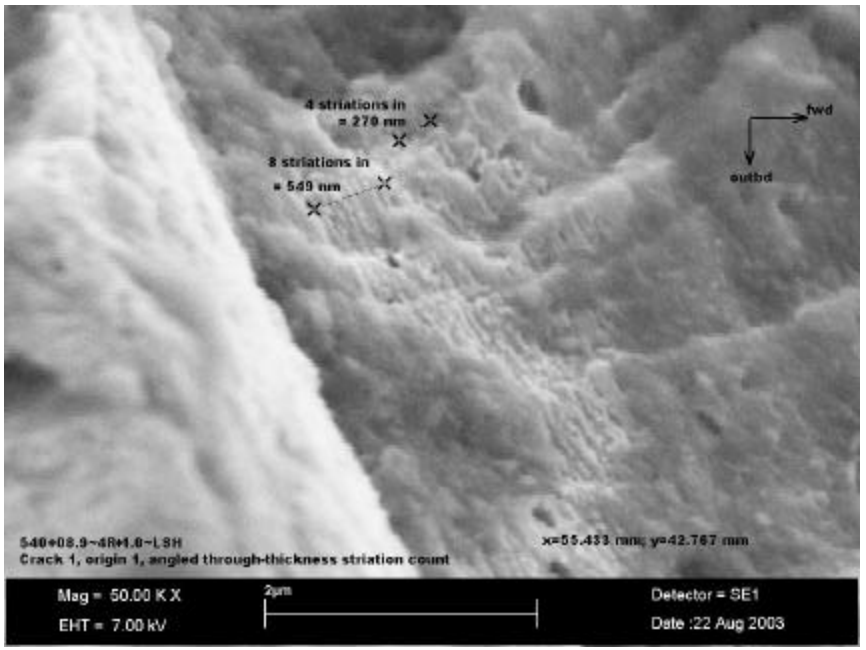




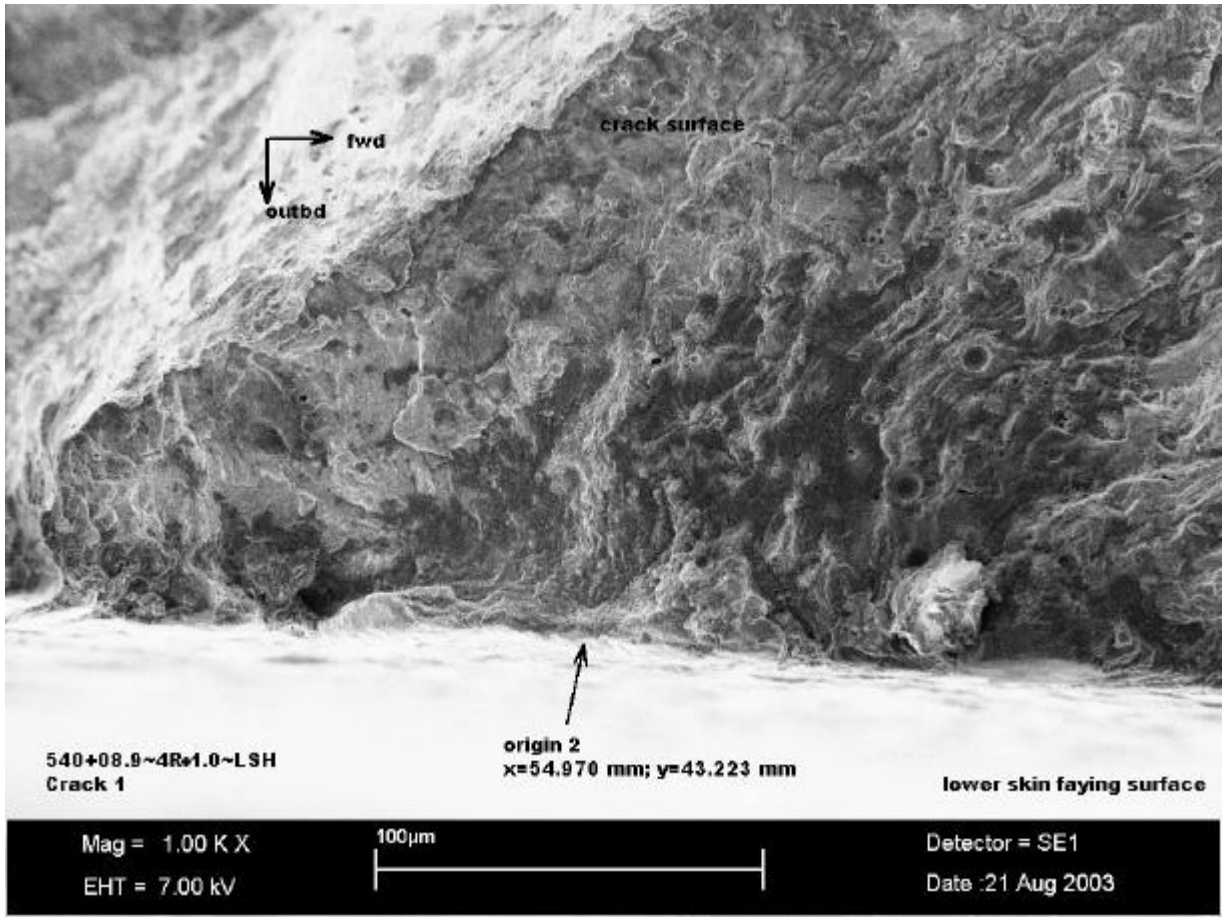
Part 3d: Scanning Electron Microscope Fractography of Cracks

Fastener hole location 540+08.9~4R+1.0~LSH Crack #1 - Origin 1



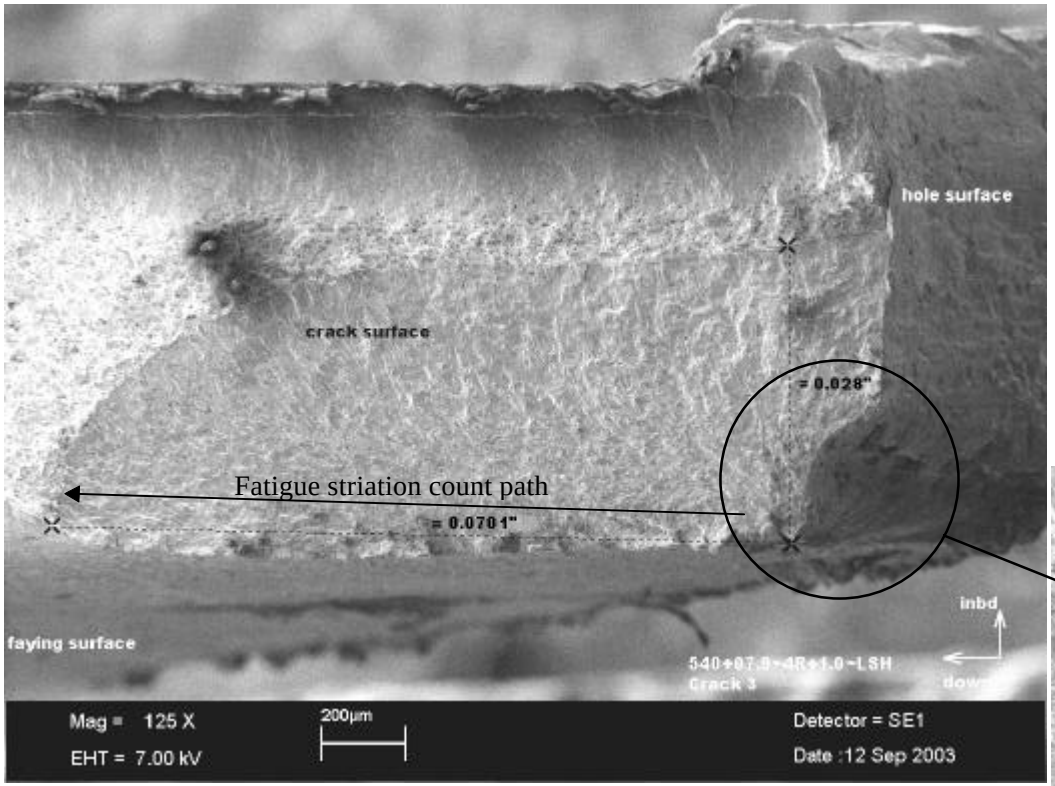


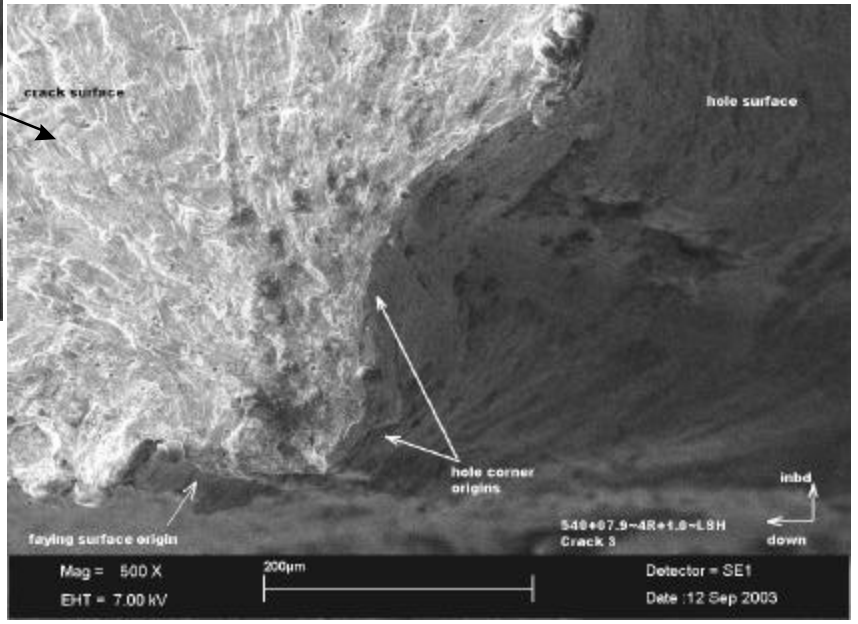
Fastener hole location 540+08.9~4R+1.0~LSH Crack #1 - Origin 1



Part 3d: Scanning Electron Microscope Fractography of Cracks

Fastener hole location 540+08.9~4R+1.0~LSH Crack #3

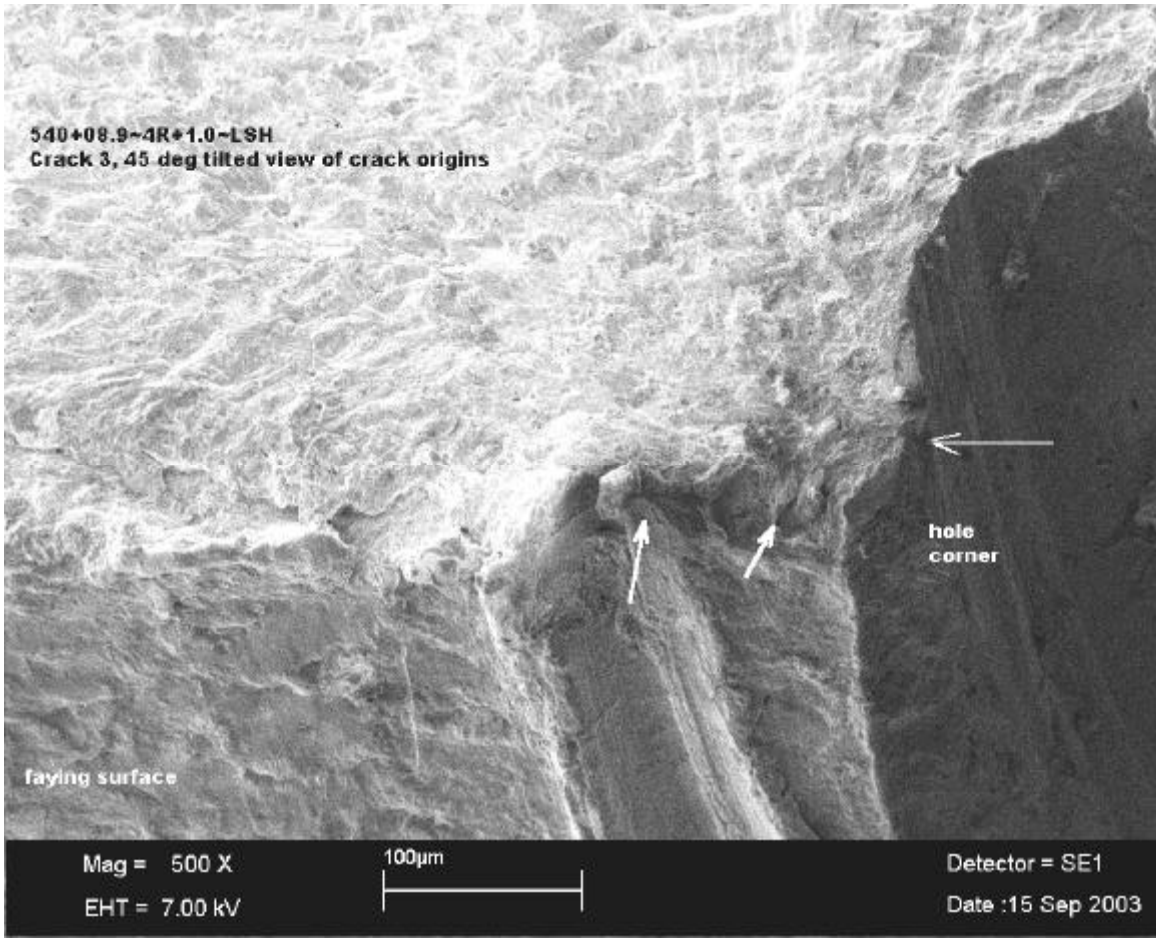




Part 3d: Scanning Electron Microscope Fractography of Cracks

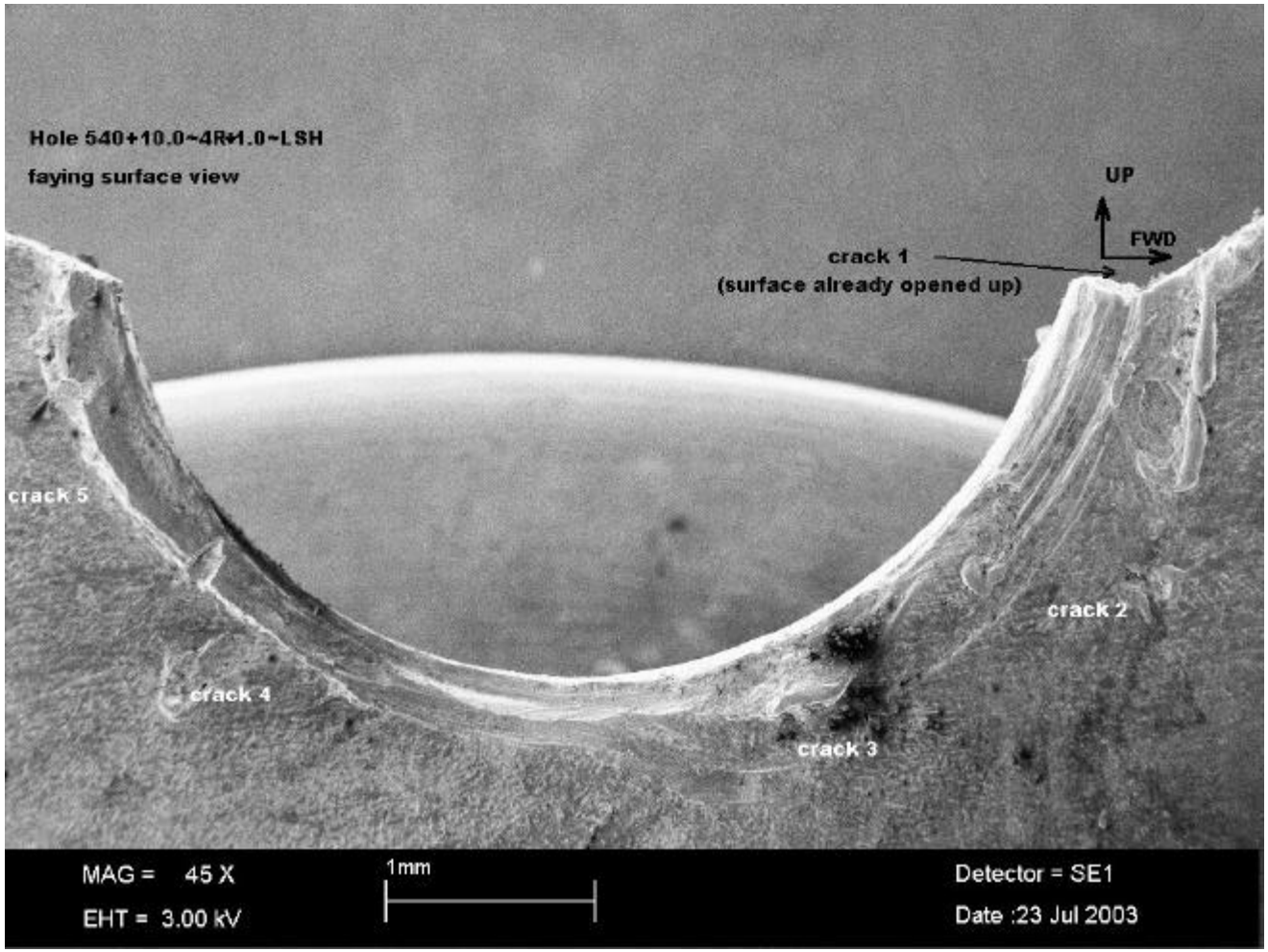
Fastener hole location 540+08.9~4R+1.0~LSH

Crack #3 - view of origin at hole corner

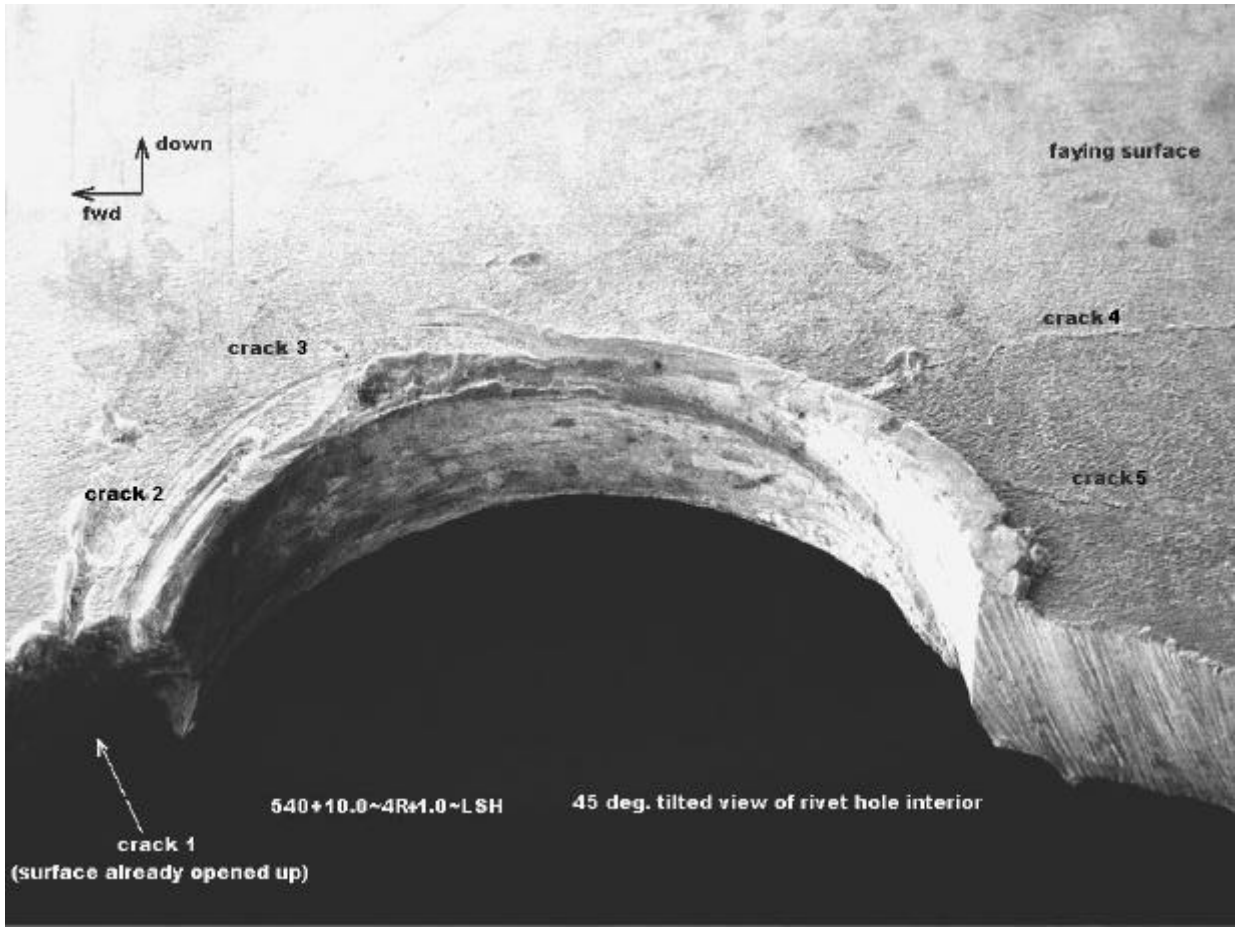


Part 3 f: Scanning Electron Microscope Fractography of Cracks

Cracks in fastener hole location 540+10.0~4R+1.0~LSH

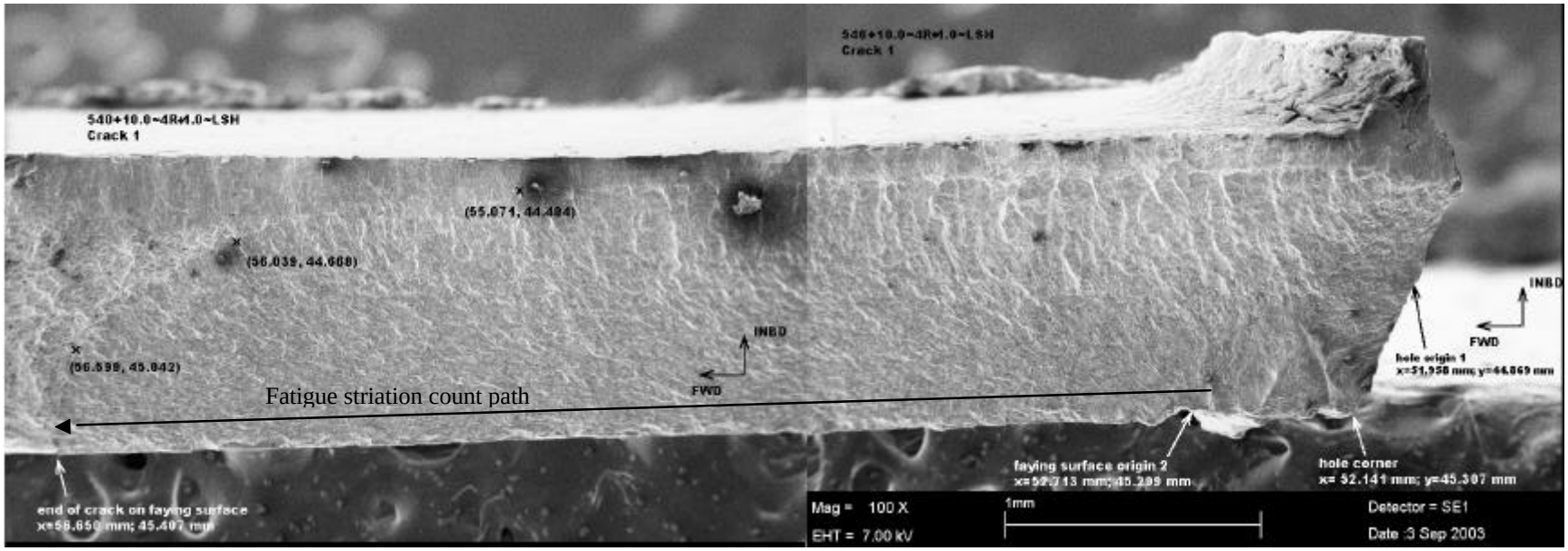


Cracks in fastener hole location 540+10.0~4R+1.0~LSH - view inside the hole



Fastener hole location 540+10.0~4R+1.0~LSH

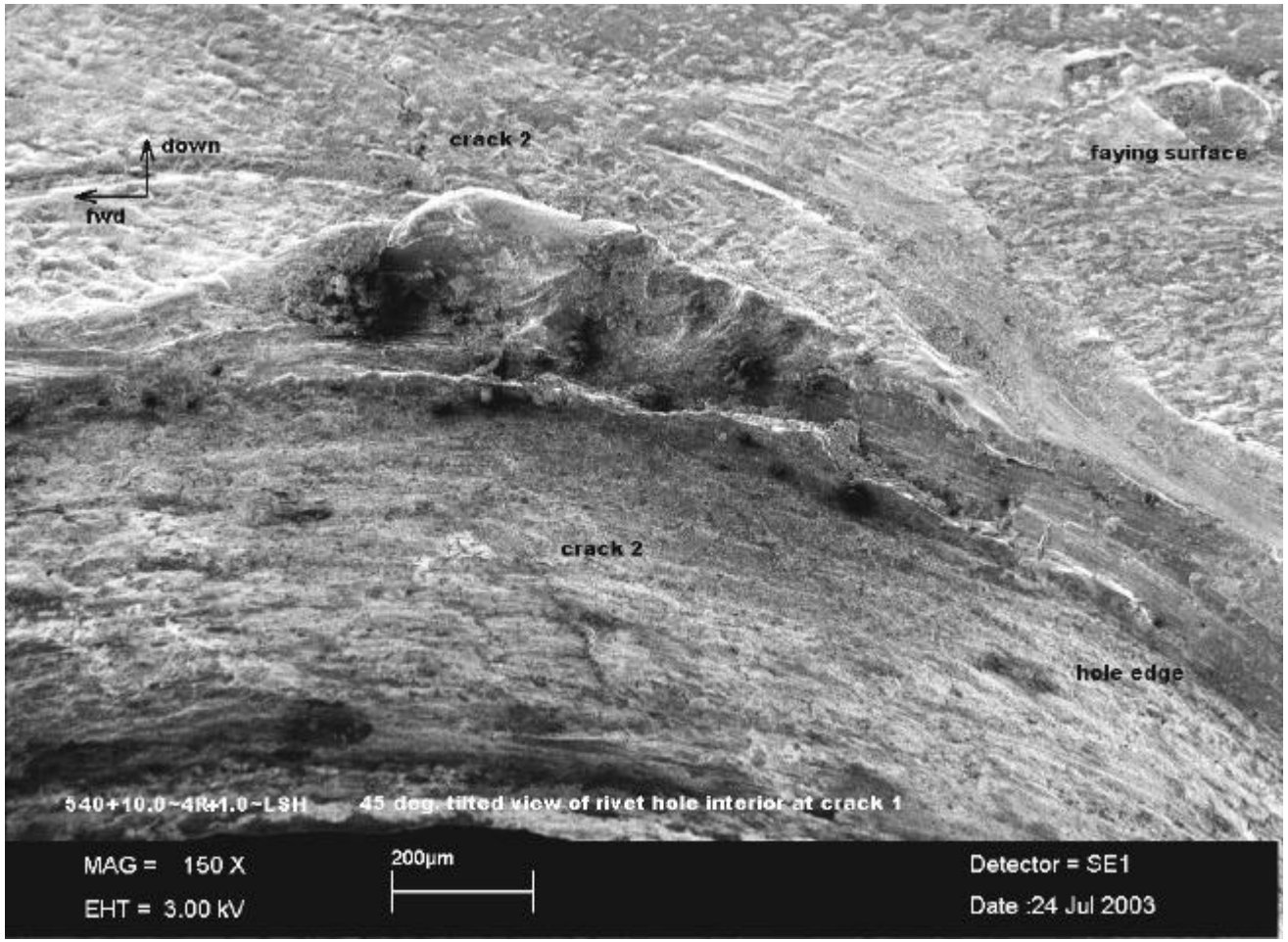
Crack #1



Part 3 f: Scanning Electron Microscope Fractography of Cracks

Fastener hole location 540+10.0~4R+1.0~LSH

Hole surface between cracks 1 and 2



Part 3 g: Scanning Electron Microscope Fractography of Cracks

Summary of Crack Origins Study

- 11 cracks in 5 lower row fastener holes have been studied so far.
- 7 of the 11 cracks had more than one origin location; i.e., they had a combination of hole surface, corner and faying surface origins and/or had multiple origins in the same region (such as multiple faying surface or multiple hole origins)
- Crack propagation fronts from the different origins were clearly defined in only two cracks.
- In these two cracks the sub-cracks from the different origins coalesced between about 0.040” to 0.070” from the hole corner
- Flaws where origins were located, where discernible, were classed into two scale categories and the following sizes:
  - Macroscopic such as gouges/grooves/scratches, seen at or below 200X, were typically of the order of 0.001 to 0.004” deep by 0.004” to 0.009” wide
  - Microscopic such as pits or breaks in the surface, seen at 1000X - 5000X, were typically of the order of 0.0002”

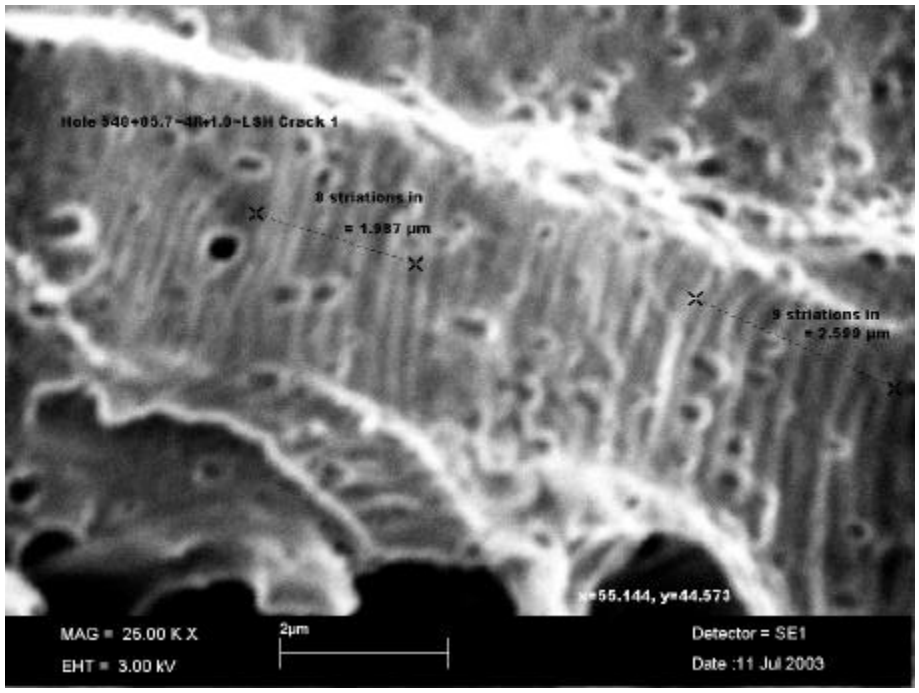
Part 3h: Scanning Electron Microscopy Fractography of Cracks

Fracture Surface Morphology and Fatigue Striations

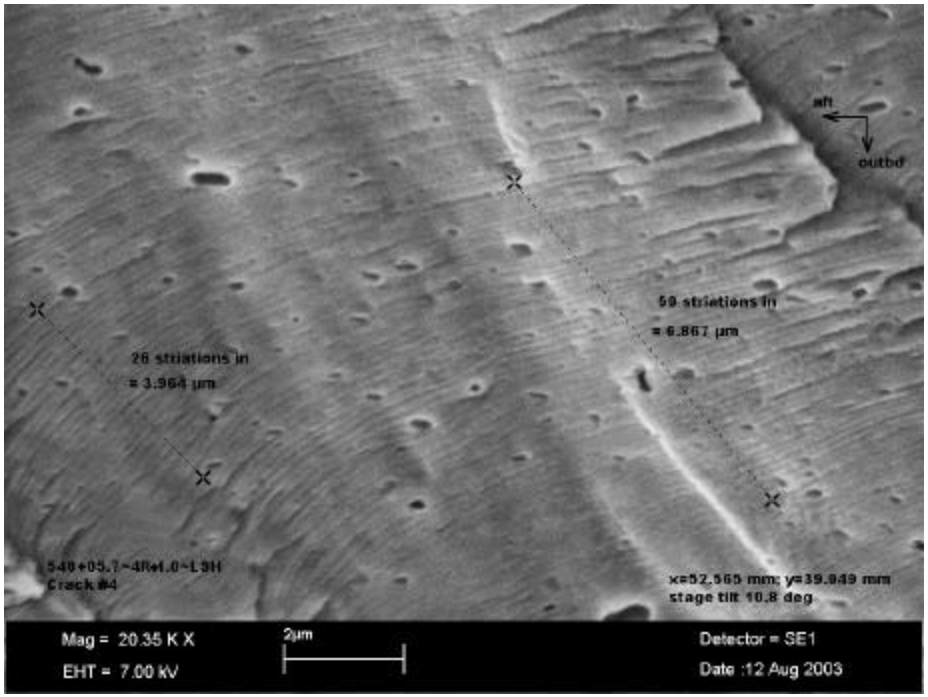
- The fracture surfaces of 10 cracks have been studied in detail so far;
- All of the cracks studied exhibited a ductile transgranular morphology with fatigue striations seen everywhere on the surface of the cracks (dimpled morphology was seen beyond the crack propagation front, corresponding to the opening-up of the crack in overstress during tear down);
- The fatigue striation micrographs have a pitted appearance - this is from the cleaning process used to remove corrosion products on the surface;
- The fatigue striations though almost always visible were not always sufficiently clear to enable counting and measuring;
- Most of the striation count measurements were made in the magnification range of 15,000 to 35,000 X, with some measurements near the crack origins made at 45,000 - 50,000 X.
- Example striations are shown in the following slides

Fastener Hole 540+05.7~4R+1.0~LSH

Examples of Fatigue Striations



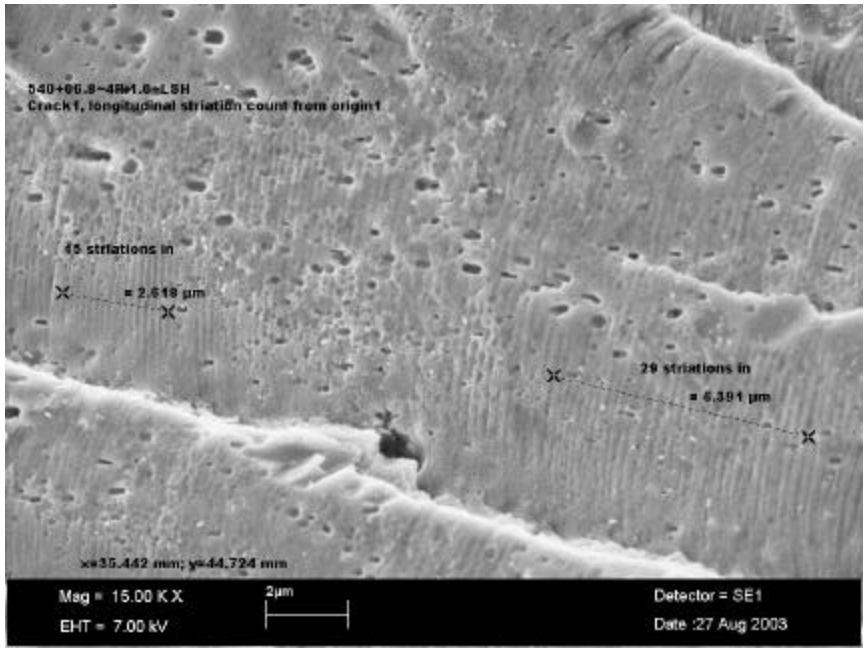
in crack 1 at a distance of 0.01” from the origin



in crack 4 at a distance of 0.015” from the origin

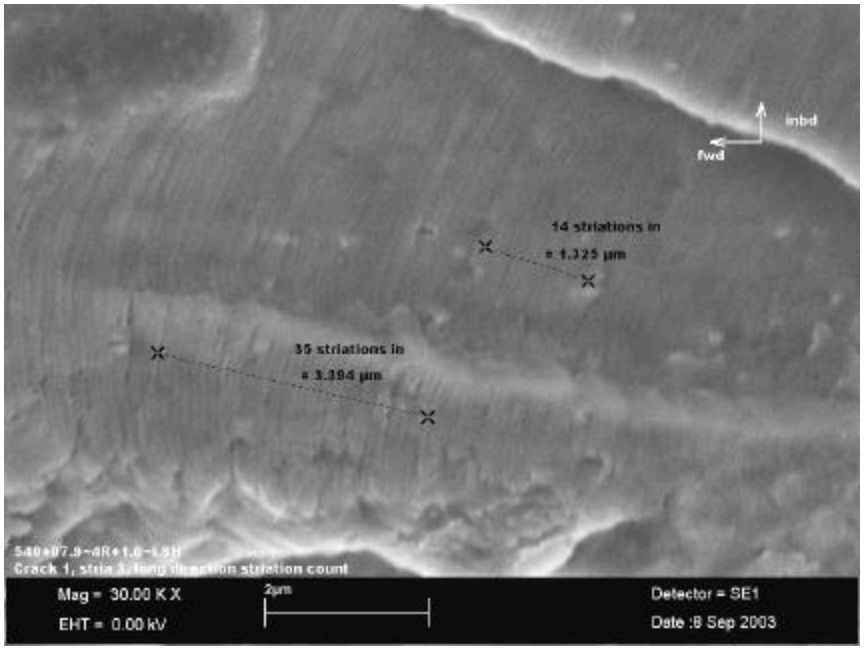
Examples of Fatigue Striations

Fastener Hole 540+06.8~4R+1.0~LSH



in crack 1 at a distance of 0.15” from the origin

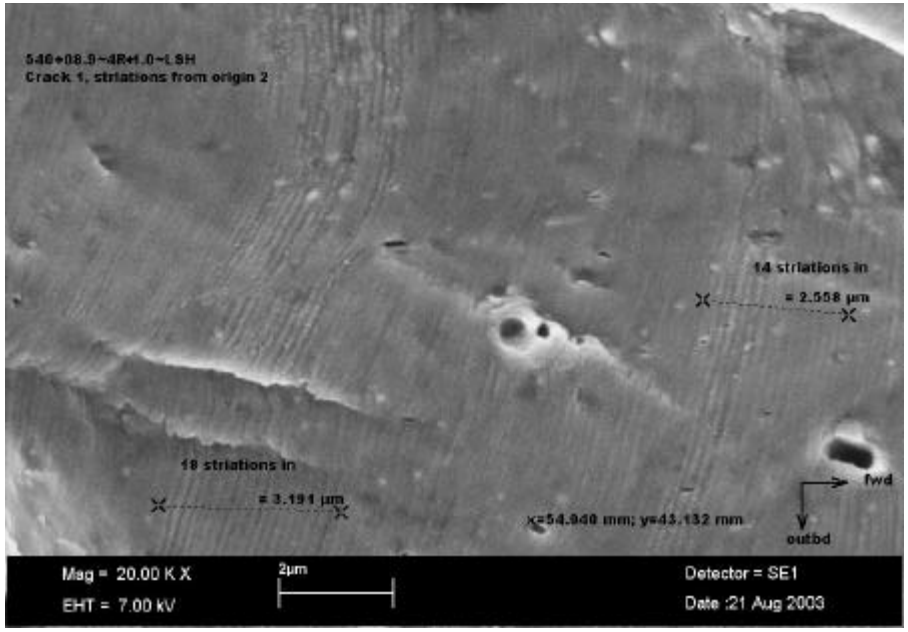
Fastener Hole 540+07.9~4R+1.0~LSH



in crack 1 at a distance of 0.008” from the origin

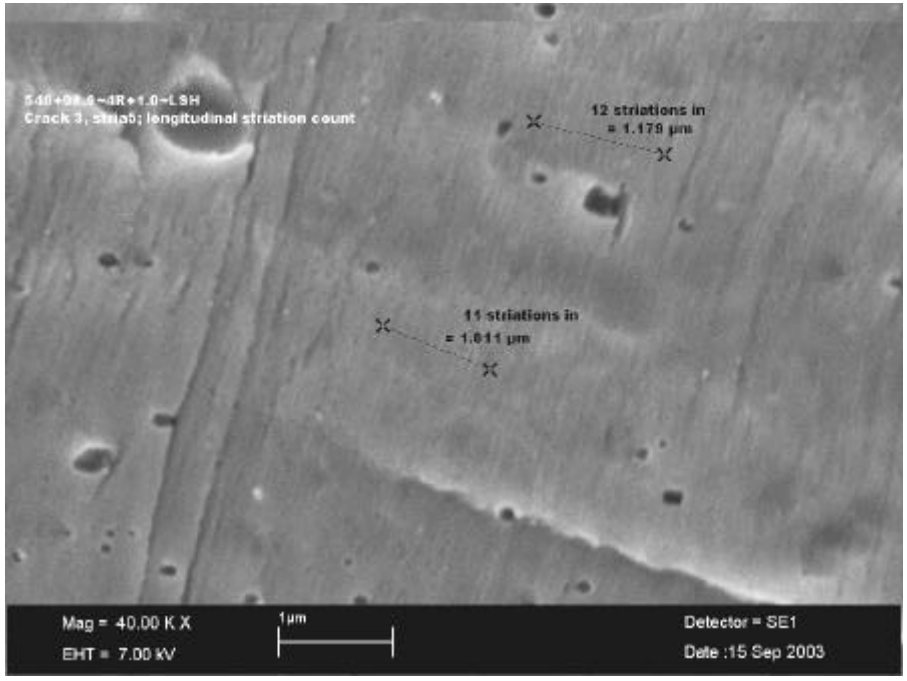
Examples of Fatigue Striations

Fastener Hole 540+08.9~4R+1.0~LSH



in crack 1 at a distance of 0.037” from the origin

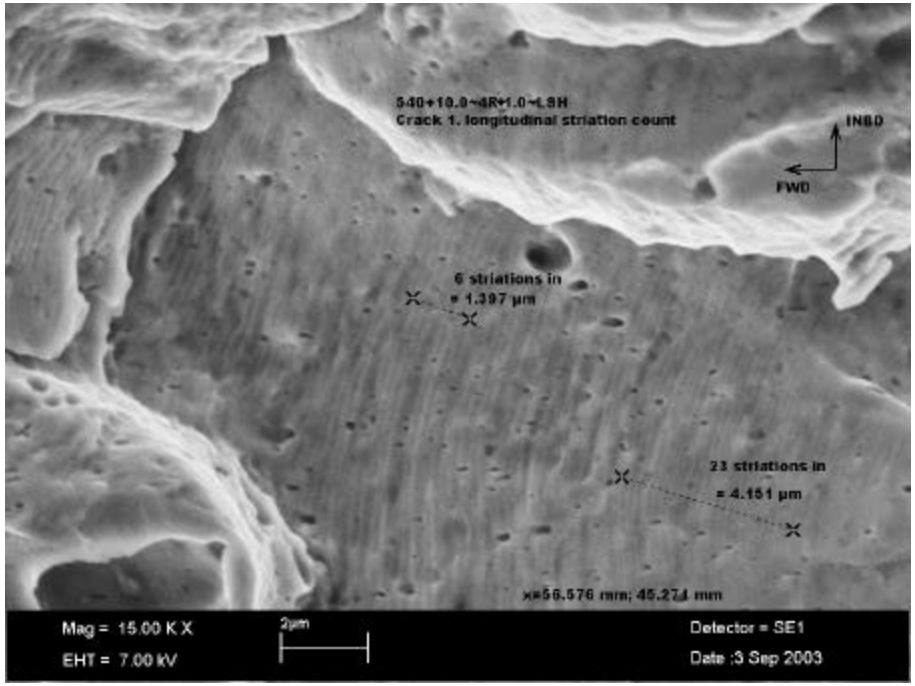
Fastener Hole 540+08.9~4R+1.0~LSH



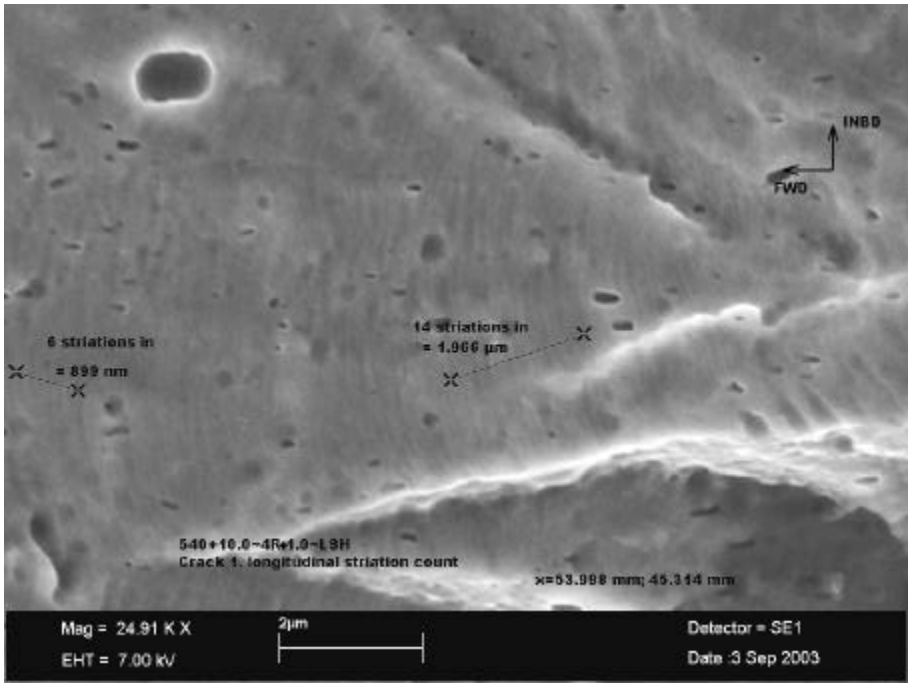
in crack 3 at a distance of 0.026” from the origin

Examples of Fatigue Striations

Fastener Hole 540+10.0~4R+1.0~LSH



in crack 1 at a distance of 0.15” from the origin

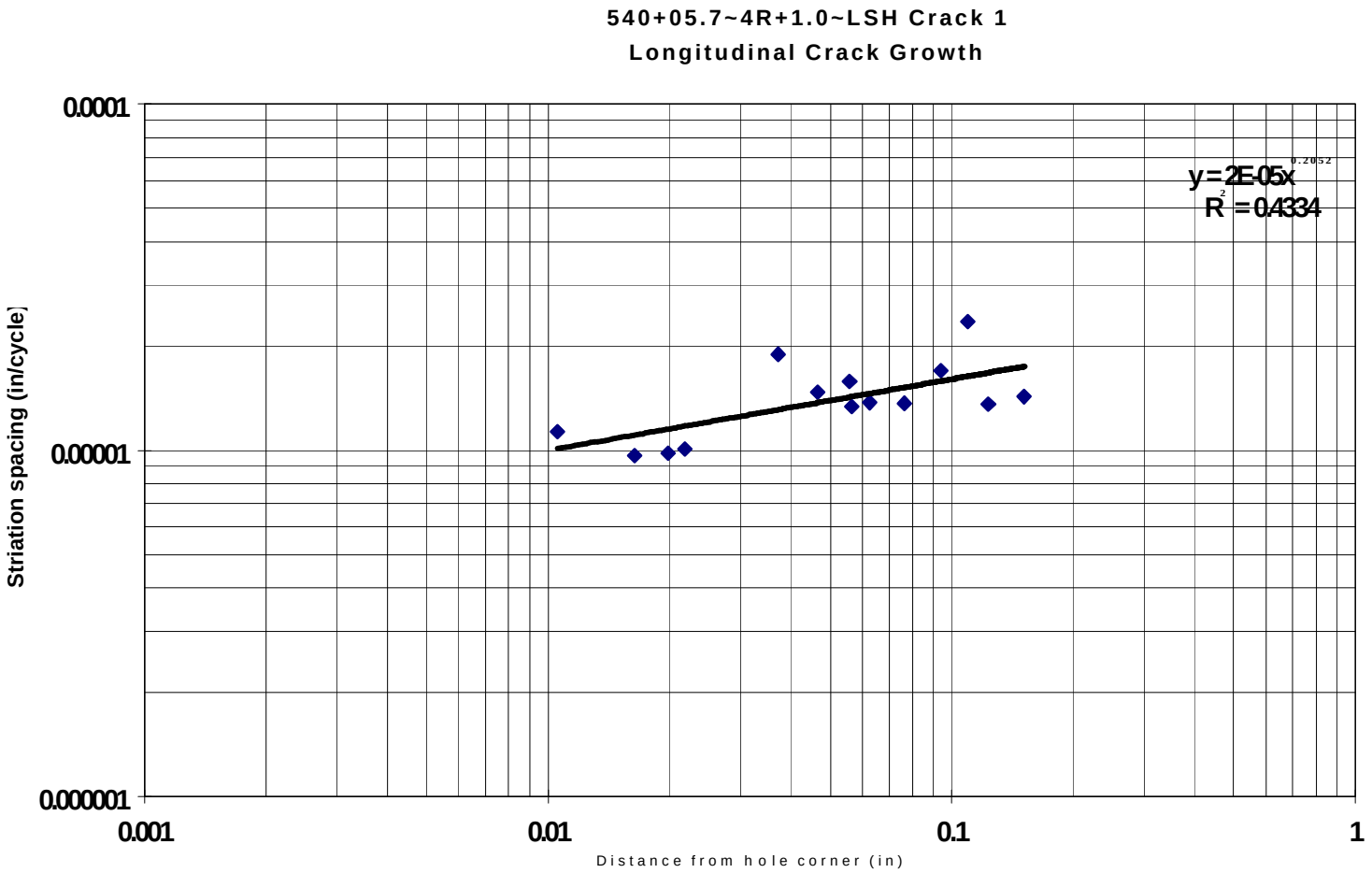


in crack 1 at a distance of 0.05” from the origin

Part 3 i: Crack Growth Rates

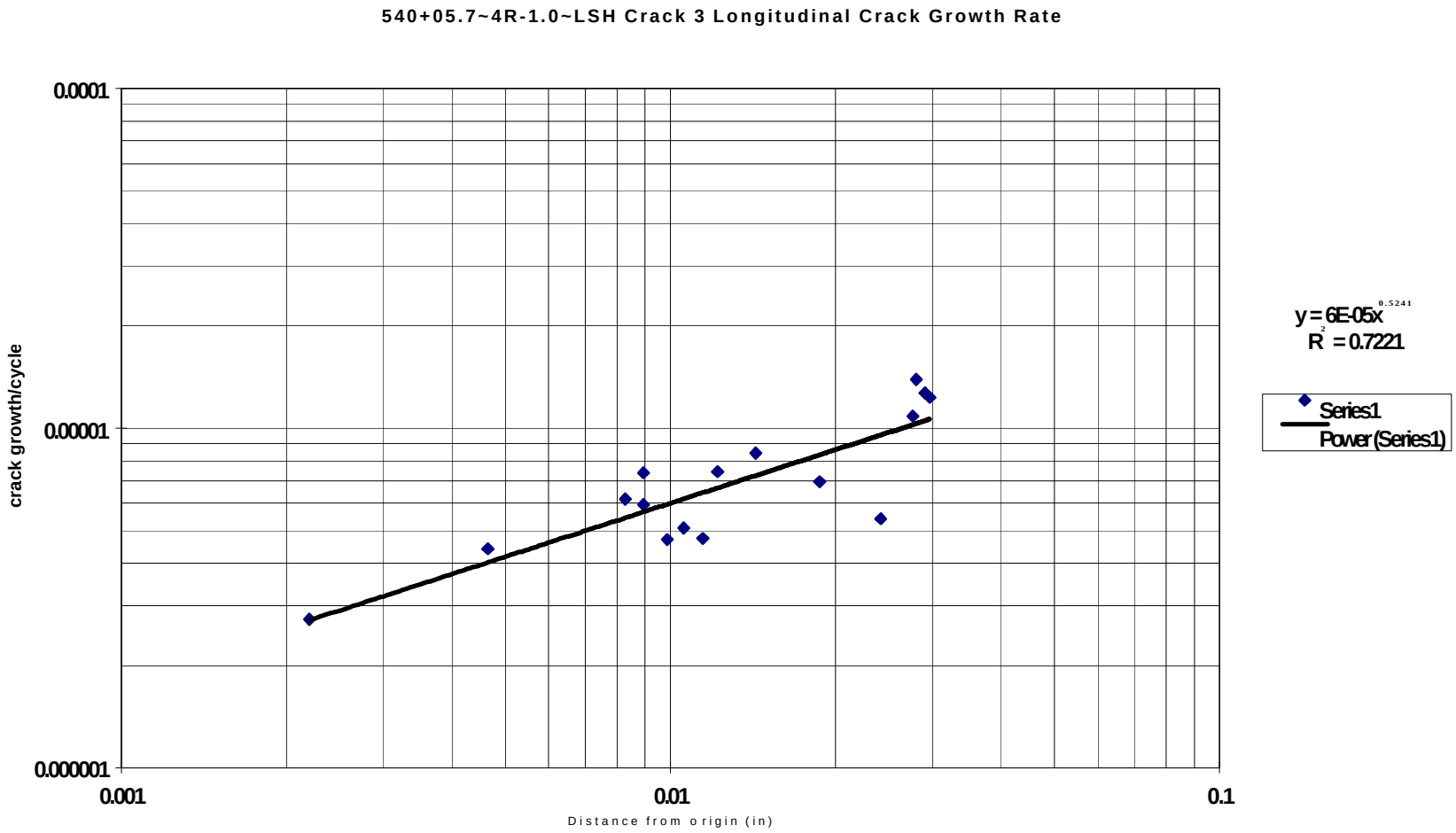
- Crack growth rate curves as a function of crack sizes were plotted for each of the 10 cracks on which striation spacings were measured (average striation spacing at each location is equivalent to the instantaneous crack growth rate at the location that the striation spacings were measured);
- Example curves are presented here, to illustrate the typical range and trend of the measurement (the micrographs of the crack surfaces may be referred to for the striation count path);
- Crack growth reconstruction was limited to estimating the total cycles of crack propagation, for each of the cracks using a power law curve fit and is summarized in a table format;

Part 3 i: Crack Growth Rates



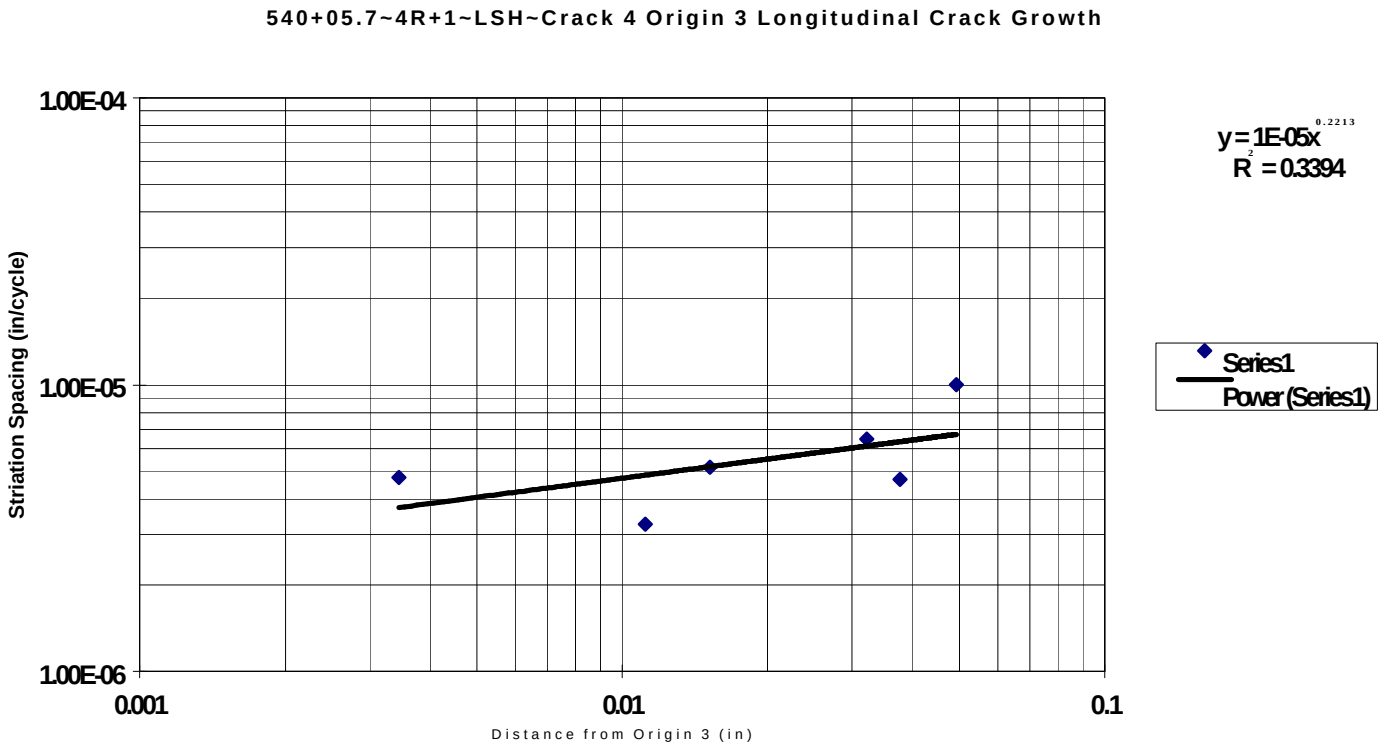
(ref. page 46 for striation count path on crack surface)

Part 3 i: Crack Growth Rates



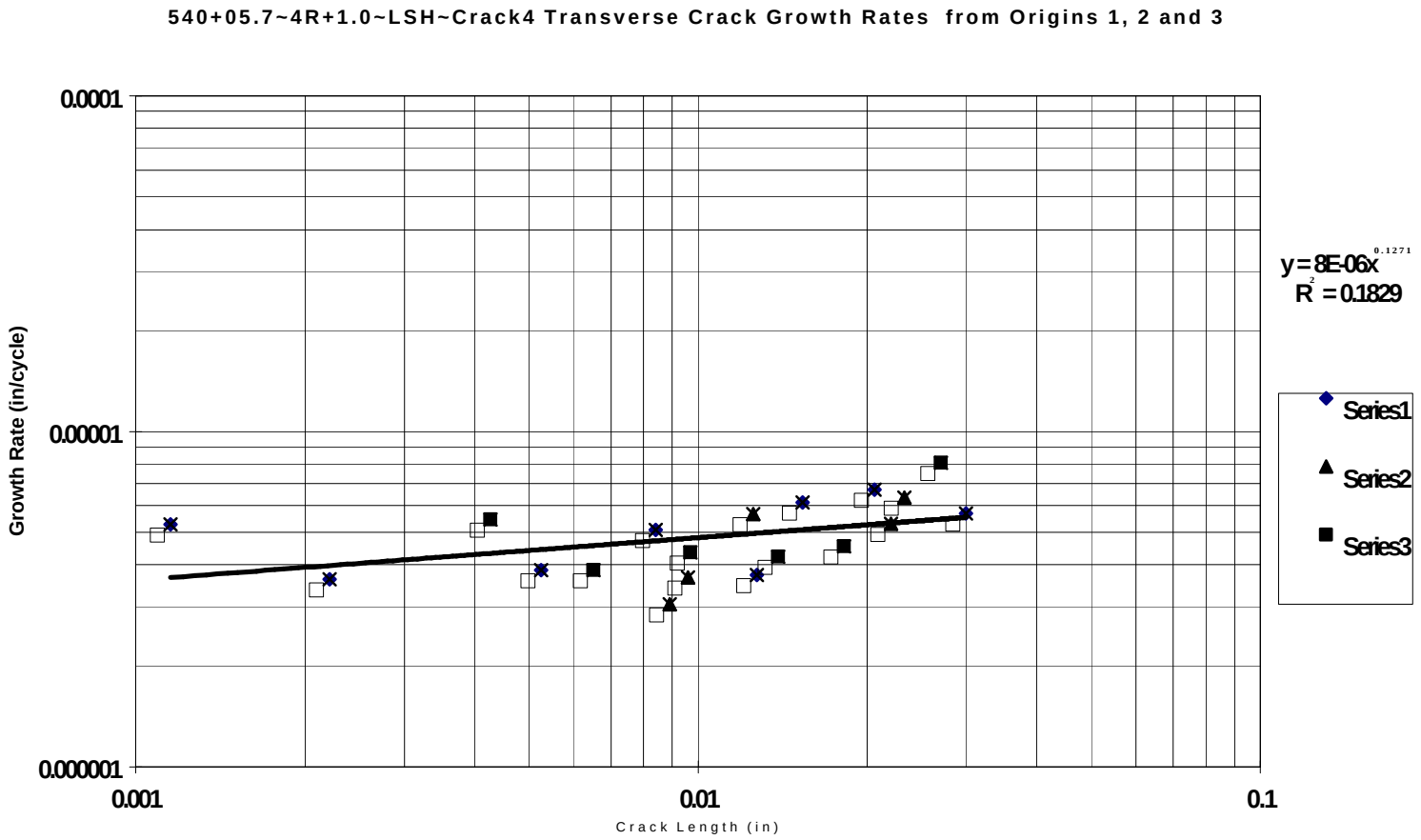
(ref. page 49 for striation count path on crack surface)

Part 3 i: Crack Growth Rates



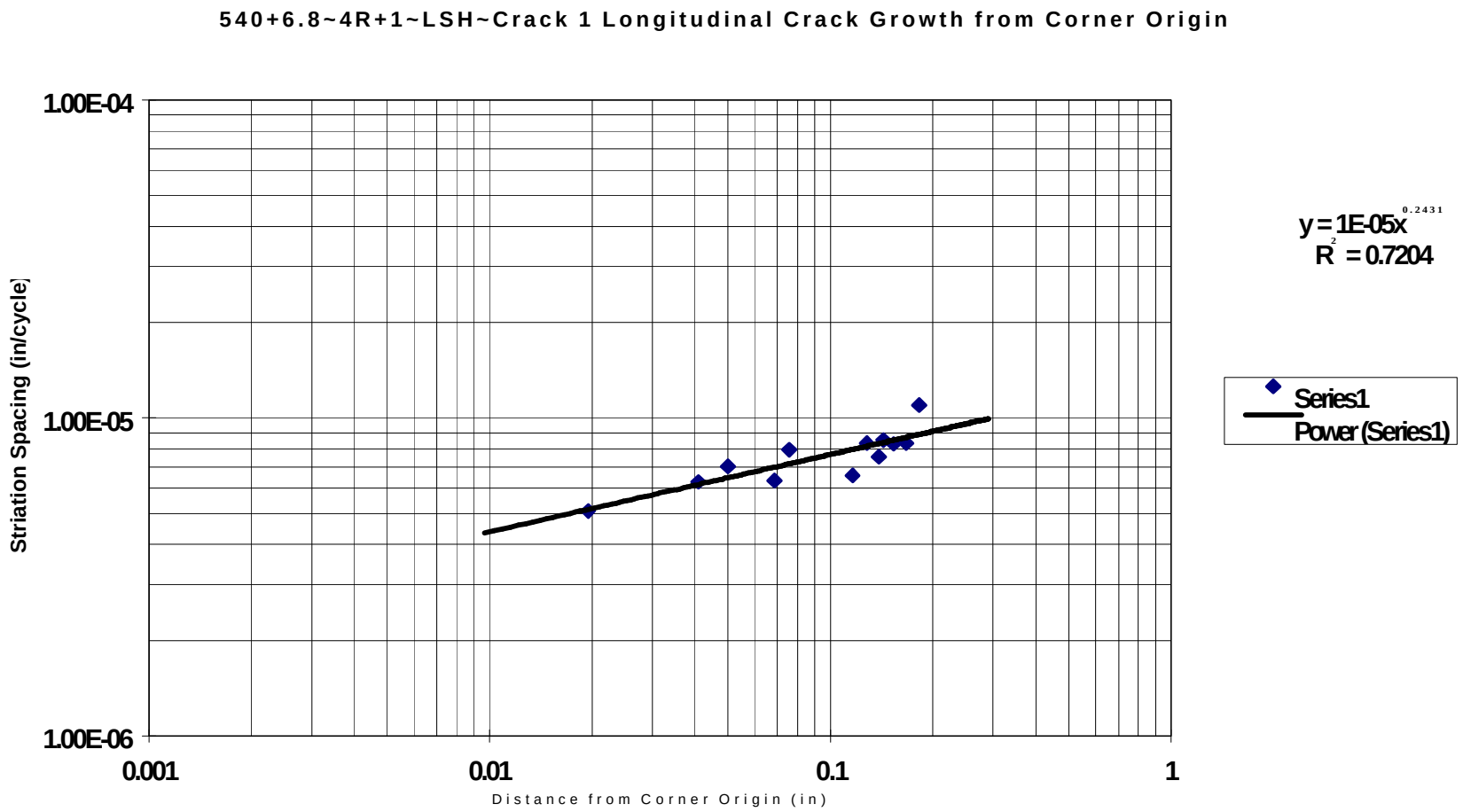
(ref. page 51 for longitudinal striation count path on crack surface)

Part 3 i: Crack Growth Rates



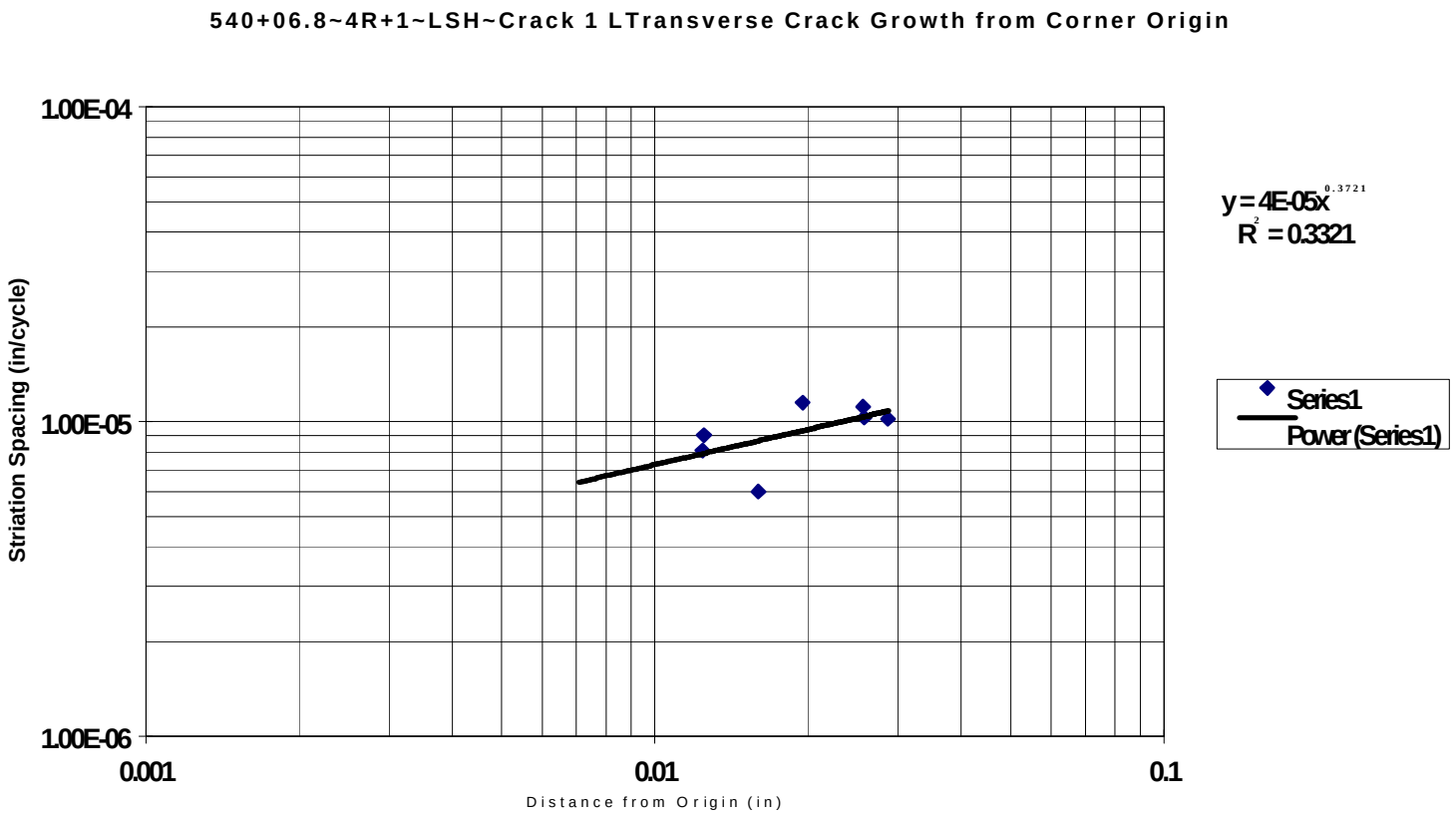
(ref. page 51 for transverse striation count paths on crack surface)

Part 3 i: Crack Growth Rates



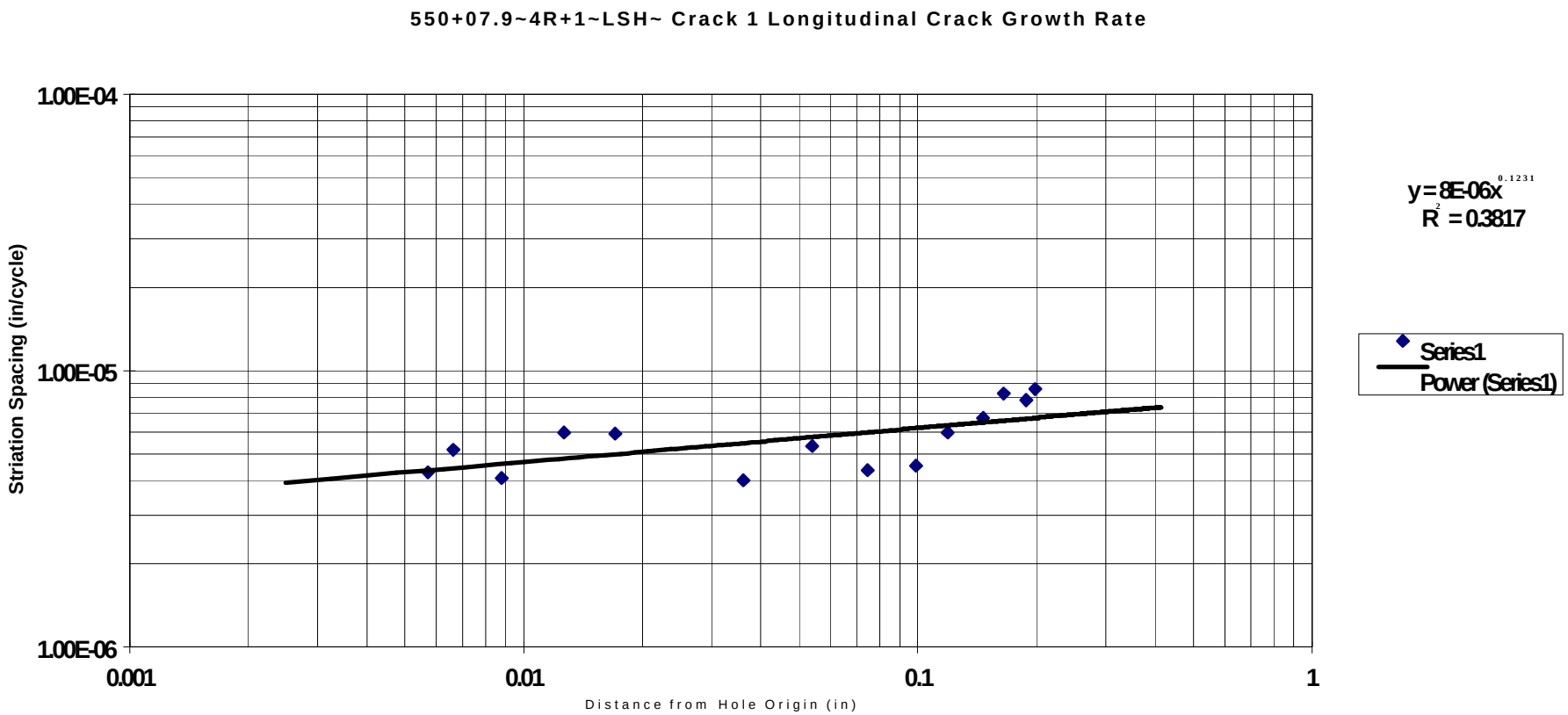
(ref. page 55 for longitudinal striation count path on crack surface)

Part 3 i: Crack Growth Rates



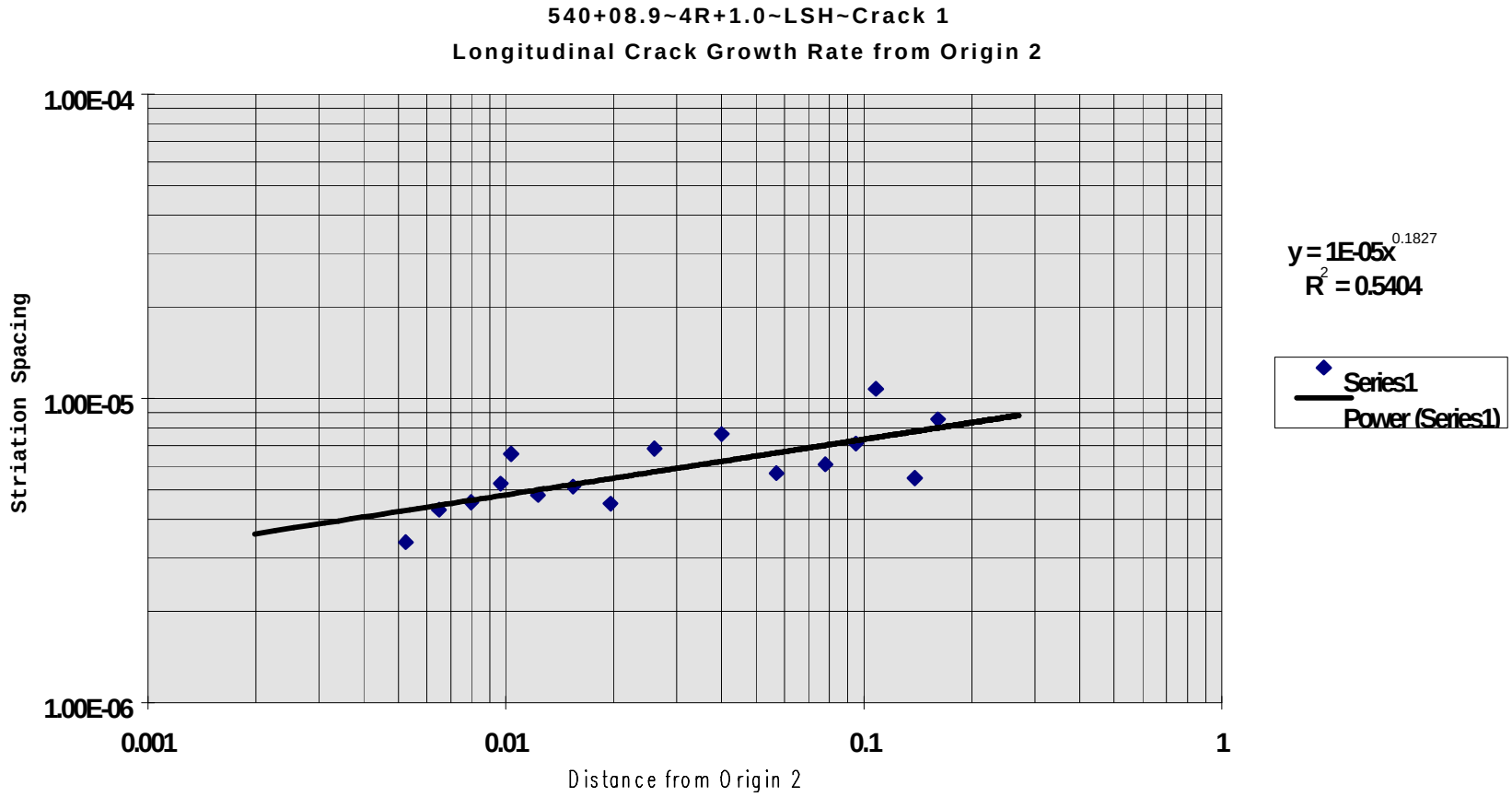
(ref. page 55 for transverse striation count path on crack surface)

Part 3 i: Crack Growth Rates



(ref. page 63 for longitudinal striation count path on crack surface)

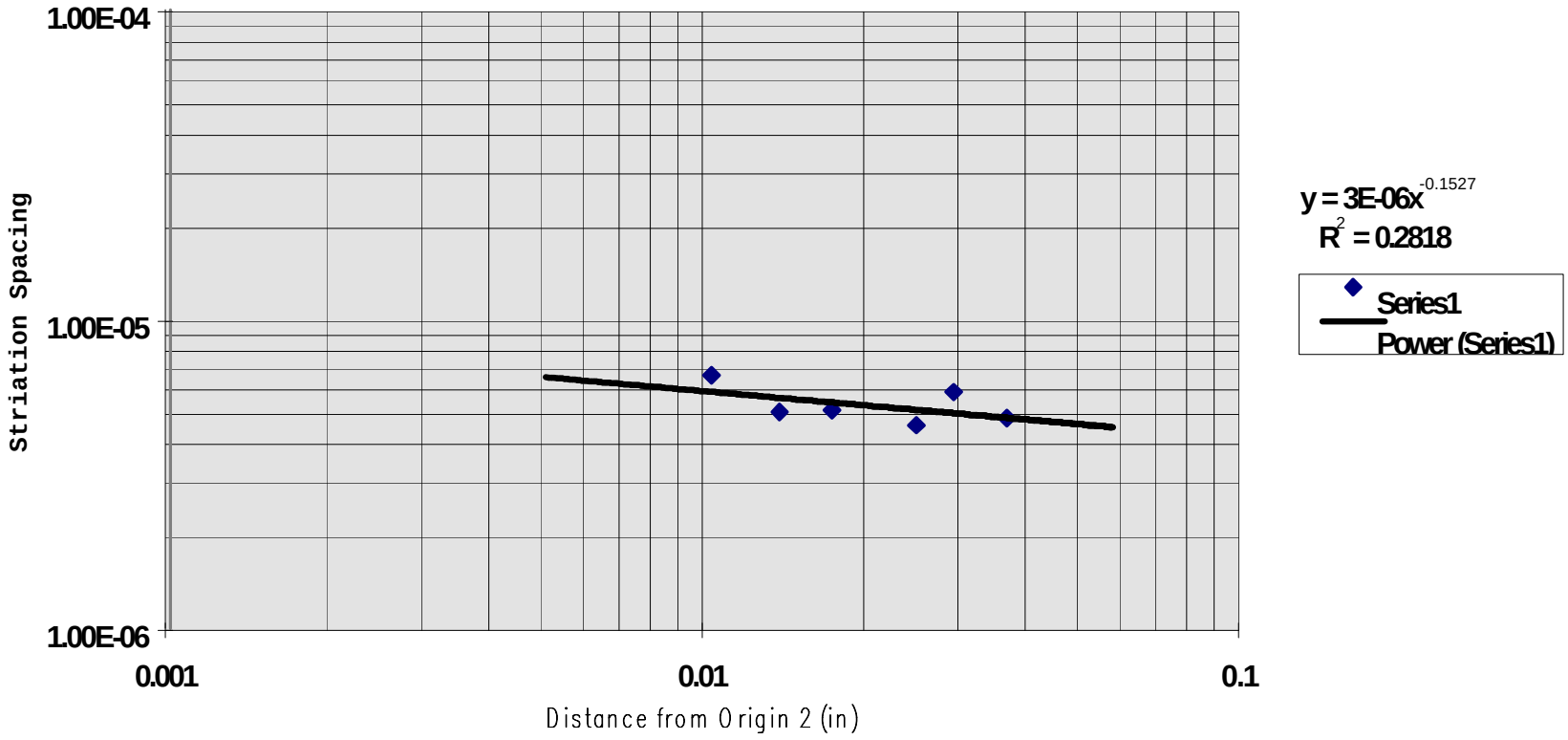
Part 3 i: Crack Growth Rates



(ref. page 69 for longitudinal striation count path from origin 2 on crack surface)

Part 3 i: Crack Growth Rates

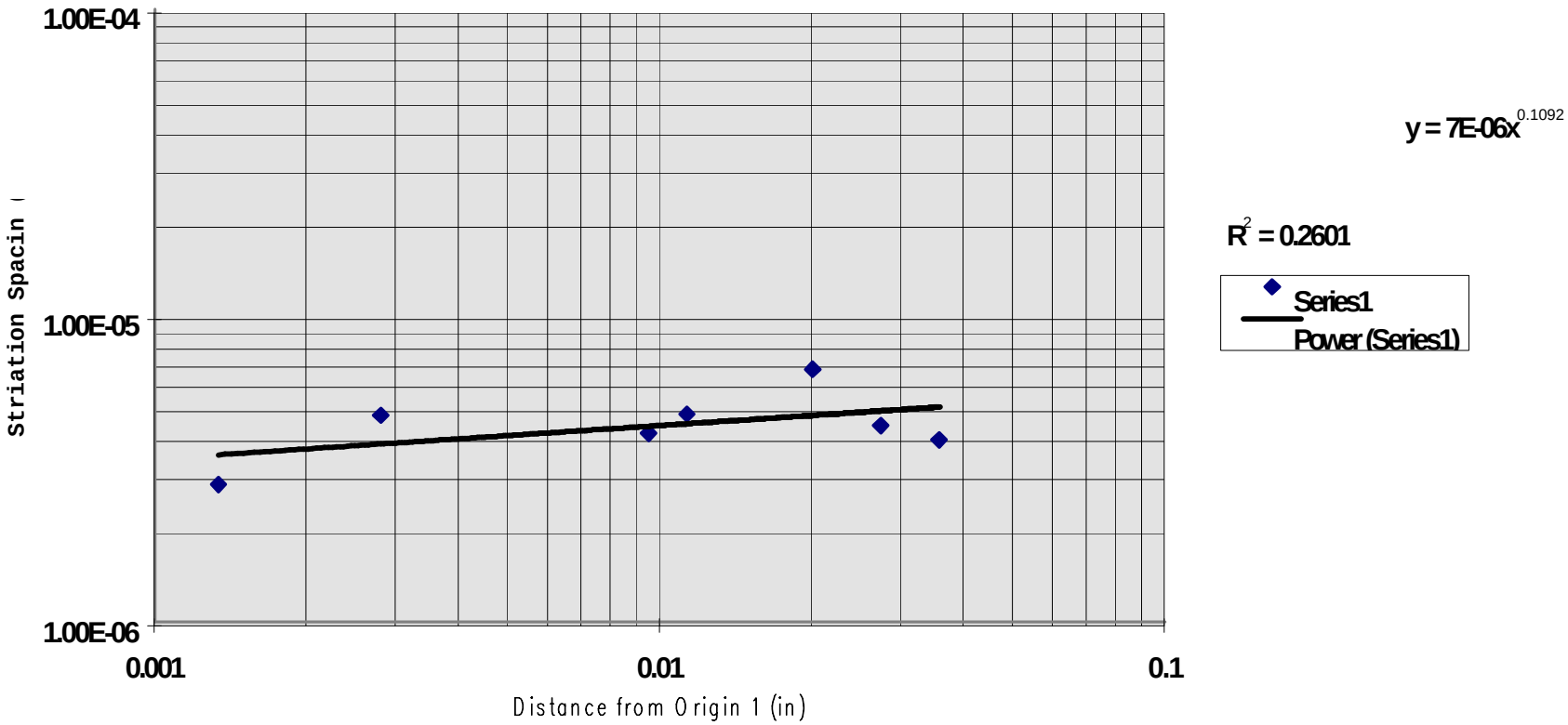
540+08.9~4R+1.0~LSH~ Crack 1 Transverse Crack Growth Rates from Origin 2



(ref. page 69 for transverse striation count path from origin 2 on crack surface)

Part 3 i: Crack Growth Rates

540+08.9~4R+1.0~LSH ~ Longitudinal Crack Growth Rates from Origin 1



(ref. page 69 for striation count path from origin 1 on crack surface)

Part 3 i: Crack Growth Rates

Summary of Crack Growth Rates and Estimated Growth Periods

LSH Hole Location	Crack #	Striation Count Path	Number of data points	Curve Fit equation	Final crack size for crack growth estimation (in)	Estimated crack growth period (cycles) starting from an initial size of 0.001in
540+05.7~4R+1.0	1	Longitudinal	14	2.0 E-5 $x^{0.2052}$	0.153	13,900
	2	Longitudinal	4	N/A (used average rate of 5.77xE-6 /cycle)	0.033	5,500
	3	Longitudinal	15	6.0 E-5 $x^{0.5241}$	0.034	5,700
	4	3 transverse paths	19	8.0 E-6 $x^{0.1271}$	0.035	7,300
		Longitudinal path	6	1.0E-5 $x^{0.2213}$	0.089	18,900
540+06.8~4R+1.0	1	Longitudinal	12	1.0E-5 $x^{0.2431}$	0.187	36,500
		Transverse	7	4.0E-5 $x^{0.3721}$	0.038	4,600
	2	Striation count not yet performed				

(Note: accuracy of final crack sizes is within +0%, -10%; will be improved after SEM re-calibration at low magnifications; crack growth period estimates are good to +/- 15%, typical of such estimates)

Part 3 i: Crack Growth Rates

Summary of Crack Growth Rates and Estimated Growth Periods

LSH Hole Location	Crack #	Striation Count Path	Number of data points	Curve Fit equation	Final crack size for crack growth estimation (in)	Estimated crack growth period (cycles) starting from an initial size of 0.001in
540+07.9~4R+1.0	1	Longitudinal	14	8.0 E-6 $x^{0.1231}$	0.217	37,000
		Transverse	5	5.0 E-5 $x^{0.5051}$	0.042	7,100
	2	Longitudinal	5	2.0 E-5 $x^{0.4515}$	0.056	16,700
540+08.9~4R+1.0	1	Long. - origin 1	7	7.0 E-6 $x^{0.1092}$	--	--
		Long. - origin 2	16	1.0E-5 $x^{0.1827}$	0.174	28,900
		Trans. - origin 2	6	3.0E-6 $x^{-0.1527}$	0.037	6,300
	3	Longitudinal	6	6.0 E-6 $x^{0.0966}$	0.070	16,533
540+10.0~4R+1.0	1	Longitudinal	8	1.0E-5 $x^{0.2647}$	0.175	37,000

Part 4: Conclusion

The findings and results of the damage characterization performed on the three lap joint bays to-date, share several common features notably:

- the presence of more than two cracks in several of the fastener holes, with cracks oriented in both the longitudinal and circumferential directions;
- machining grooves and other damage present in the hole edges at the faying surface of the lower skin, with a large number of the holes having similar rivet (mis)installations;
- multiple origins in a majority of the cracks, with the origins located variously on the faying surface, the hole corner and the hole surface;

These common threads of findings suggest that a generalized model may be developed, that would take into account or account for these findings, which would be applicable to understanding the damage causing mechanisms at all the lower row fastener holes in the lower skin of the lap joints.